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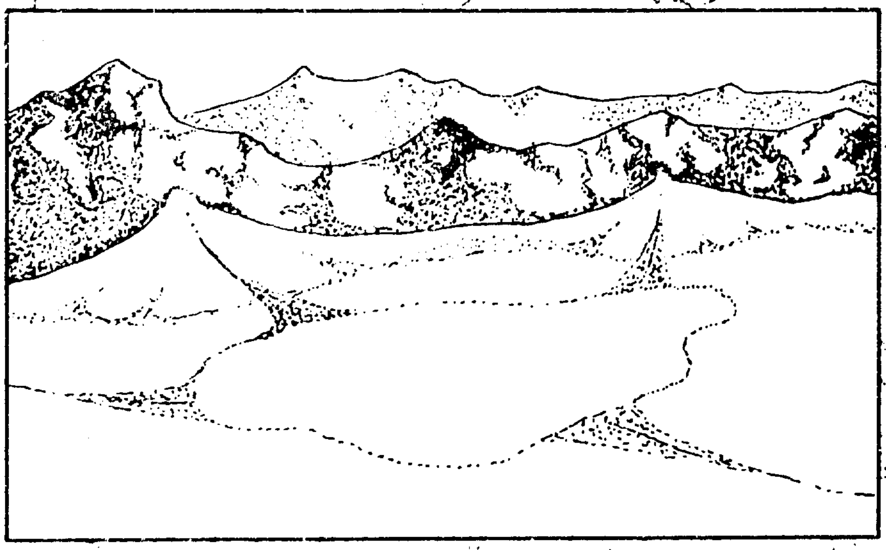
GEOLOGY AND HYDROLOGY OF SELECTED PLAYAS IN WESTERN UNITED STATES



EDITOR

WARD S. MOTTS

CONTRIBUTORS

DAVID CARPENTER
DAVID B. MATZ
CHARLES G. GROAT
WARD S. MOTTS
ROBERT F. WALKER

UNIVERSITY OF MASSACHUSETTS — AMHERST

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Editor

WARD S. MOTTS

Contributors

David Carpenter, Charles G. Groat,
David Matz, Ward S. Motts, Robert F. Walker

GEOLOGY DEPARTMENT
UNIVERSITY OF MASSACHUSETTS, AMHERST, MASSACHUSETTS 01002

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Contract Monitor: James T. Neal, Captain, USAF
Terrestrial Sciences Laboratory
(Now at U.S. Air Force Academy)

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
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UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS 01730

I dedicate this publication to my wife Dona, and to the wives of the other authors whose patience and help made this study possible.

ABSTRACT

The playas studied during this investigation may be divided into "fine-grained playas" (Rogers, Rosamond, Coyote Playas, California, and Big Smoky Playa, Nevada) and "coarse-grained playas" (Troy Playa, California, and Clayton Playa, Nevada). The "fine-grained playas" are characterized by: (1) deposits of medium silt through fine clay size, (2) slow artesian and capillary movement of water through the surface, (3) mostly smooth, hard surfaces, and (4) current formation of giant desiccation polygons in many of the playas. The "coarse-grained playas" are characterized by: (1) deposits of sand, silt, and in some cases evaporites, (2) rapid capillary discharge, (3) a water table that nearly coincides with the playa surface, and (4) soft, surficial sediments.

The surface morphology of most playas is related to several factors including the rate of capillary discharge producing puffy ground, and the frequency of surface-water flooding producing smooth, hard ground. Also, capillary discharge combined with deposition of mud from floods has transformed roots and water-transported plants into highly irregular knobby ground in some playas, including Clayton. Playas are dynamic landforms that change (1) over many years because of long-term climatic changes and man-made changes in the environment and (2) over a period of days or months because of short-term changes in precipitation and other climatic effects. A long-term change has been the expansion of many playas in recent years at the expense of their adjacent desert flats.

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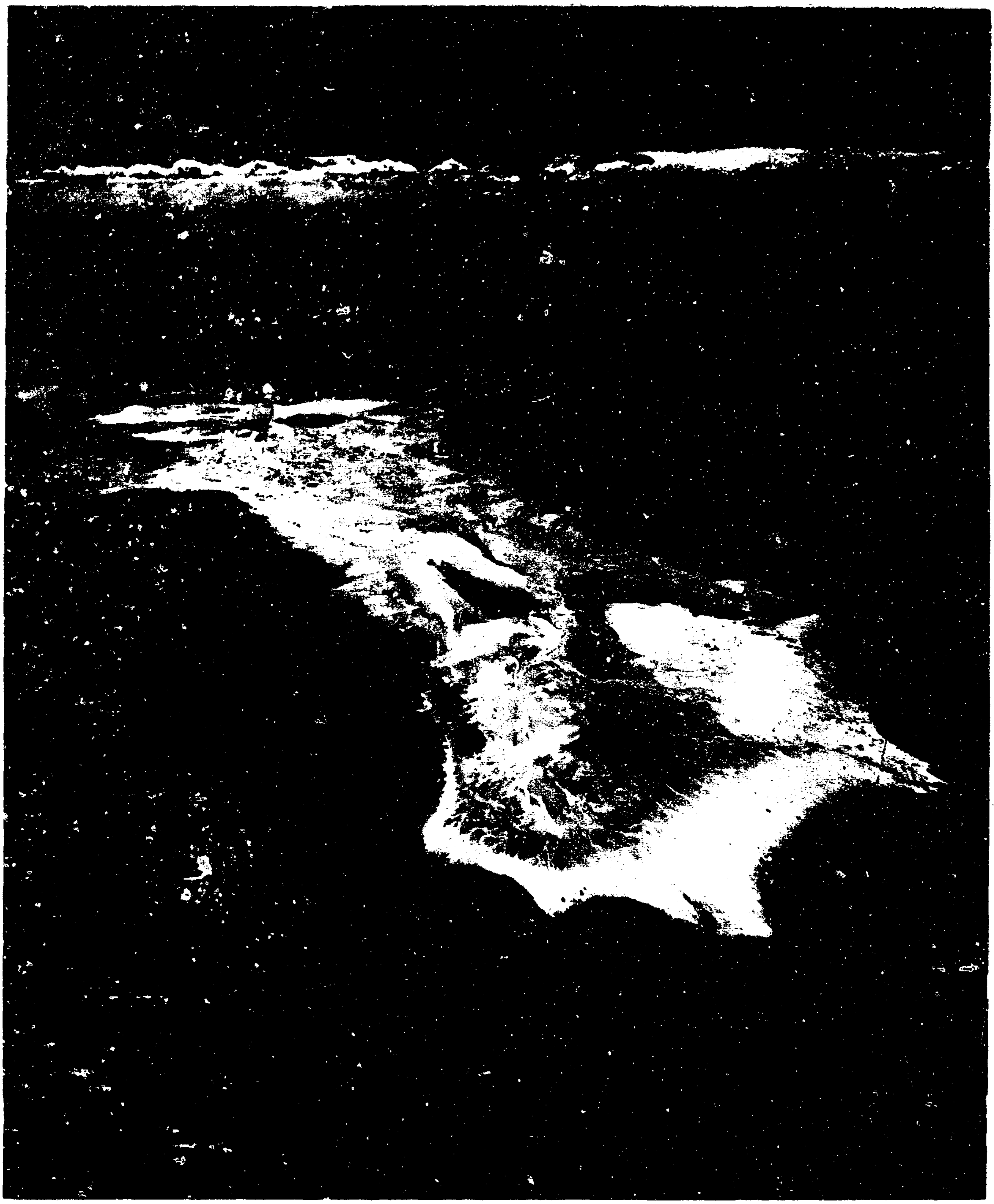

FRONTISPIECE

Clayton Playa, Nevada, in July 1965, a playa discharging large amounts of ground water from an extensive recharge area. The white color is from salt deposited by capillary discharge of ground water. (See Chap. 6.)

INTRODUCTION TO PLAYA STUDIES

Ward S. Motts

INTRODUCTION

Playas and closed valleys are geologically unique because they are among the few places where it is possible to have total interior drainage of both ground water and surface water. Because some playas are enclosed by ground-water divides as well as topographic divides, they are the ultimate resting place for all chemical constituents carried in solution by ground water and for all suspended materials carried by streams. Consequently, playas are significant areas for studies of sedimentation and geomorphology, especially for those studies concerning relationships of deposition and deflation.

Purposes, Methods, and Area of Investigation

Two main objectives determined the scope of the present study: first, to study many playas on a reconnaissance level in order to obtain a "broad view" and a basic subdivision of playas (Phase 1) and second, to study selected playas in detail in order to obtain information on individual playas of different types (Phase 2). During the first phase, the author studied about 125 playas in California, Nevada, Utah, southern Oregon, Arizona, and New Mexico, some of which are shown in Figure 1*. Most of the playas are in

---

*In this report the term playa will be used where the geomorphic form is a playa as defined in this section. On many topographic maps of the U. S. Geological Survey the descriptive term "lake" is used following the local usage. It would be misleading and confusing to use the term "lake" for playa in a report of this type especially because true lakes occur near

the Basin and Range Province, and a few are in the High Plains Province of eastern New Mexico and western Texas. Aerial photographs and topographic maps of these playas were studied in the office followed by field investigations of 1 to 3 days at each playa. From the reconnaissance investigations knowledge was obtained of major playa types in western United States, and selected playas were chosen for more detailed study. Reports of the reconnaissance phase include studies by Motts (1965) and Neal and Motts (1967).

During the second phase of the project the following playas were studied in detail as theses by graduate students under the guidance of the author at the University of Massachusetts: Troy Playa, California, by Charles Groat (1967), M.S.; Coyote Playa, California, by David Hagar (1966), Ph.D.; Big Smoky Playa, Nevada, by Robert Walker (1966), M.S.; South Panamint Playa, California, by Carlos Carrenza (1965), M.S.; and North Panamint Playa, California, by Philip Durgin (manuscript in preparation), M.S. The author was assisted by David Carpenter in a drilling program on Rogers, Rosamond, Coyote, North Panamint, and South Panamint Playas in the summers of 1965 and 1966; parts of this study as well as additional field work will be used by David Carpenter as partial fulfillment for a Master's Degree. Some results of the test drilling program were discussed in Motts and Carpenter (1968). The reports of North Panamint and South Panamint Playas have not been completed for publication; however, some references to these studies will be made.

Geologic and geomorphic maps of the selected playas were made in the field on topographic maps and aerial photographs; some detailed maps were

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playas in Nevada and in other parts of the West. For example, the terms "Troy Lake" and "Coyote Lake" appear on U. S. Geological Survey maps; however, this report will use the terms "Troy Playa" and "Coyote Playa," since these latter areas are true playas.

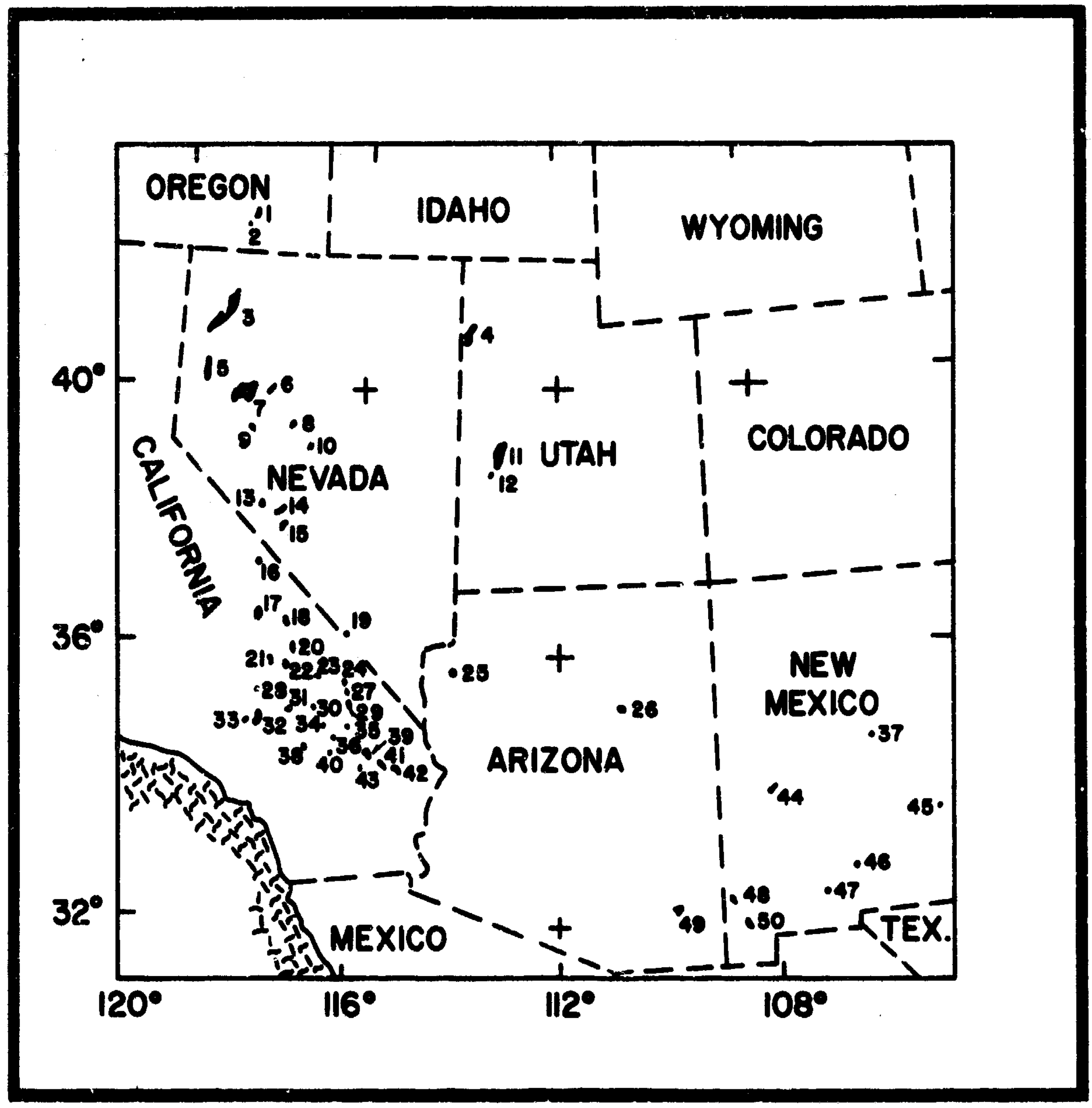

Figure 1. Index map showing location of playas studied in the reconnaissance phase of this investigation. See Table 1 for names of playas.

Table 1. Reference list for playas shown on Figure 1. Geographic names may indicate "lake" or some other term; however all locations shown are playas.

Map No.	Playa
48	Alkali Flat (playa in Animas Valley), Cal.
1	Alvord Desert, Ore.
2	Alvord Lake, Ore.
14	Big Smoky Playa (Blair Junction), Nev.
10	Big Smoky Valley (Millett) Playa, Nev.
3	Black Rock Desert, Nev.
4	Bonneville Salt Flats, Utah
39	Bristol Lake (playa), Cal.
35	Broadwell Lake, Cal.
41	Cadiz Lake, Cal.
7	Carson Sink (playa and lake complex), Nev.
21	China Lake, Cal.
15	Clayton Playa, Nev.
13	Columbus Salt Marsh, Nev.
30	Coyote Lake, Cal.
43	Dale Lake, Cal.
42	Danby Lake, Cal.
16	Deep Springs Lake, Cal.
31	Harper Lake, Cal.
6	Humboldt Salt Marsh, Nev.
28	Koehn Lake, Cal.

Map No.	Playa
9	Labou Flat, Nev.
46	Lake Lucerno, New Mex.
36	Lavic Lake, Cal.
23	Leach Lake, Cal.
38	Lucerne Lake, Cal.
45	Marley Playa, New Mex.
18	North Panamint Lake, Cal.
17	Owens Lake, Cal.
37	Pago Playa (Estancia Valley), New Mex.
50	Playas Lake Playa, New Mex.
25	Red Lake, Ariz.
32	Rogers Lake, Cal.
33	Rosamond Lake, Cal.
44	San Augustin Plains, New Mex.
22	Searles Lake, Cal.
11	Sevier Lake, Utah
24	Silurian Lake, Cal.
27	Silver Lake, Cal.
8	Smith Creek Playa, Nev.
29	Soda Lake, Cal.
40	Soggy Lake, Cal.
20	South Panamint Lake, Cal.
19	Stewart Valley Playa, Cal.
34	Troy Lake, Cal.
47	Uvas Valley Playa, New Mex.
12	Wah Wah Valley Hardpan, Utah
49	Wilcox Dry Lake, Cal.
5	Winnemucca Lake, Nev.
26	Winslow Playas, Ariz.

made by plane table. Stakes were placed as control points for periodic observations in Pago Playa (Estancia), New Mexico; Troy Playa, Rosamond Playa, Rogers Playa, and North Panamint Playa, California. As part of the second phase, auger holes were drilled by hand to depths of 20 feet, cores were taken to depths of 30 feet by a hammer-driven coring rig of the drop type, and trenches were dug to depths of 10 feet.

During the summers of 1965 and 1966, cores and sediment samples were taken by a power-driven rotary rig on Rogers, Rosamond, Coyote, North Panamint, and South Panamint Playas. Depths of these test holes ranged from 30 to 275 feet. Soil samples were taken at 5 to 10 foot intervals for gravimetric soil-moisture analyses, which were made at the sedimentation laboratory at the University of Massachusetts. Also detailed size and mineralogical analyses of test cores, auger samples, and other samples were made at the University of Massachusetts. The water levels and heights of potentiometric* (piezometric) surfaces were measured in water wells and test holes by steel tape. The chemical characteristics of some water samples were analyzed by use of a Hach kit and a conductance meter. Some samples were analyzed by the Water Resources Division of the United States Geological Survey.

The authors of this publication gratefully acknowledge the project monitor, Captain James T. Neal, and Mr. Gerry Cabaniss, whose help and support facilitated all aspects of research on this publication. Reviews of the entire publication by Captain Neal, Charles Groat, and Marvin Saines and work on some illustrations by Richard Heeley are greatly appreciated. Special thanks are given to Mrs. Joann Chandler for her excellent secretarial and editorial work on the final report.

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*"Potentiometric" surface is used in the sense that Hubbert (1952, p. 1974) used the term as the surface defined by the elevations to which water ultimately rises in wells penetrating either confined or unconfined aquifers.

Previous Investigations

Previous investigations of playas may be divided into two categories: first, studies in which playas are part of a broader geological investigation, and second, studies that are specifically related to playa geology. Stone (1965, p. 9-10) refers to many investigations of the former category. Investigations of the latter category dealing solely with playas are much fewer in number. Russell (1883) briefly discussed playas of western United States. Bailey (1904) studied desert lands of southern California. Foshag (1926) made the first classification of playas from his work on saline lakes of California and suggested that they be subdivided into moist types and dry types. Ekblaw (1927) studied characteristics of clastic deposits in several dry lakes of California and Nevada. Thompson (1929) further developed the ideas of Foshag and divided playas into moist, dry, and crystal body types. Blackwelder (1931) concluded from his study of Danby Lake in California that playa surfaces are lowered by deflation. Some sediments of Rosamond Playa, California, were analyzed by Hamilton (1951). Stone (1956) made a comprehensive investigation of playas in California, Nevada, Arizona, and New Mexico and presented a workable and practical classification of the playa surfaces. Snyder (1962) made a hydrologic classification of valleys based on surface drainage and subsurface drainage. An Air Force publication, <u>Geology, Mineralogy, and Hydrology of United States Playas</u> (1965) includes six articles: Neal (1965a) presented a playa classification based upon lithology and surface type; Kerr and Langer (1965) discussed the mineralogy in the Mojave Desert of playa crusts--this study was later published in the Journal of Sedimentary Petrology (Langer and Kerr, 1966); Motts (1965) discussed hydrologic types of playas in closed valleys and some relationships of hydrology to playa geology;

Cabaniss (1965) made some geophysical studies of playa basins; and Neal (1965b) studied air photo characteristics of playas. In Playa Surface Morphology: Miscellaneous Investigations (1968), Neal (1968a) discussed playa surface changes at Harper Lake, California; Motts and Carpenter (1968) reported on test drilling on Rogers, Coyote, Rosamond, and Panamint Playas; Krinsley, Woo, and Stoertz (1968) described the geological characteristics of seven Australian playas; Krinsley (1968) described the geomorphology of playas in northern Iran; and Neal (1968b) discussed satellite monitoring of playa surfaces.

Neal and Motts (1967) discussed some recent geomorphic changes in playas including the nature and formation of giant desiccation polygons. Further information on giant desiccation polygons are described by Neal, Langer, and Kerr (1968). To my knowledge the most significant work concerning playas outside the United States has been made by Fritz Jaeger (1942) who studied the lime-pan playas of the Kalahari Desert and presented a classification in which he divides African playas into salt pans, salt-free pans, and lime pans.

PLAYAS AND PLAYA GEOLOGY

Definition of the Term Playa

Most American geologists would probably consider a playa to have four characteristics: (1) an area occupying a basin or topographic valley of interior drainage, (2) a smooth barren surface that is extremely flat and has a low gradient, (3) an area infrequently containing water that occurs in a region of low rainfall where evaporation exceeds precipitation, and (4) an area of fairly large size (generally more than 2000-3000 feet in diameter). The barren surface, devoid of vegetation and abundant gravel, is a distinctive feature of "playa", which in Spanish means shore or beach. Thousands of small, topographically enclosed areas ranging from a few feet to several hundred feet in diameter are scattered throughout western United States, yet one would hesitate to call them playas. The term "microplaya" (Durgin, 1968, manuscript in preparation) is appropriate for these smaller areas with playa characteristics.

Playas occupy the lowest parts of enclosed basins and are a special case of the broader category of topographically enclosed valleys. A playa is dry most of the time; the term playa lake is used when water temporarily covers the surface. On the other hand, if water is frequently present in the valley the term lake is appropriate. The length of time that water remains in a valley can be conveniently described by the "flooding ratio" (Motts, 1965, p. 76). A yearly flooding ratio can be defined as the number of days per year the playa contains water/365. In some cases a ten-year flooding ratio is of greater value than the yearly ratio since a longer time would offset erratic variations of precipitation. If the yearly flooding ratio is

0.33 or less for several years, most geologists would probably call the valley area a playa; however, if the flooding ratio is greater than 0.66 they would probably call the area a lake (Table 2). The flooding ratio is of greater value than merely defining a playa because the amount of deposition or erosion of a given playa is related to this ratio. Continuous deposition occurs in lakes; whereas little deposition and active erosion occur in playas of the Mojave Desert. The exact relationship between the flooding ratio and the amount of deposition is not known and may vary with different playas in different climatic and geographic regions.

Geomorphic and Hydrologic Setting of Playas

The geomorphic features of numerous individual playas in the Basin and Range province may be divided into the broad categories of alluvial slopes, desert flat, and playa (Fig. 2). Alluvial slopes extend from the mountain bedrock to the more gentle slopes of the desert flat. Alluvial slopes have gradients averaging 2°-3° (Clements, 1957, p. 61 and 76) but in some places they range up to 7° (Thornbury, 1956, p. 284). Alluvial slopes may be further subdivided into (1) pediments, which are underlain by bedrock with a thin alluvial veneer (0-20 feet thick), and (2) bajadas formed by coalescing alluvial fans and underlain by thick alluvium. In many places, pediment surfaces gradually merge into bajada surfaces with no pronounced change of gradient. Desert flats, generally underlain by thick bajada deposits, extend from the base of alluvial slopes to the margin of the playas. In contrast to the barren playas, desert flats are covered with sand, fine gravel, and desert vegetation. Gradients of desert flats range from 13 to 100 feet to the mile, about 15 feet to the mile for larger flats and 50 feet to the mile for smaller flats (Clements, 1957, p. 53). Many desert flats and alluvial slopes are broken by

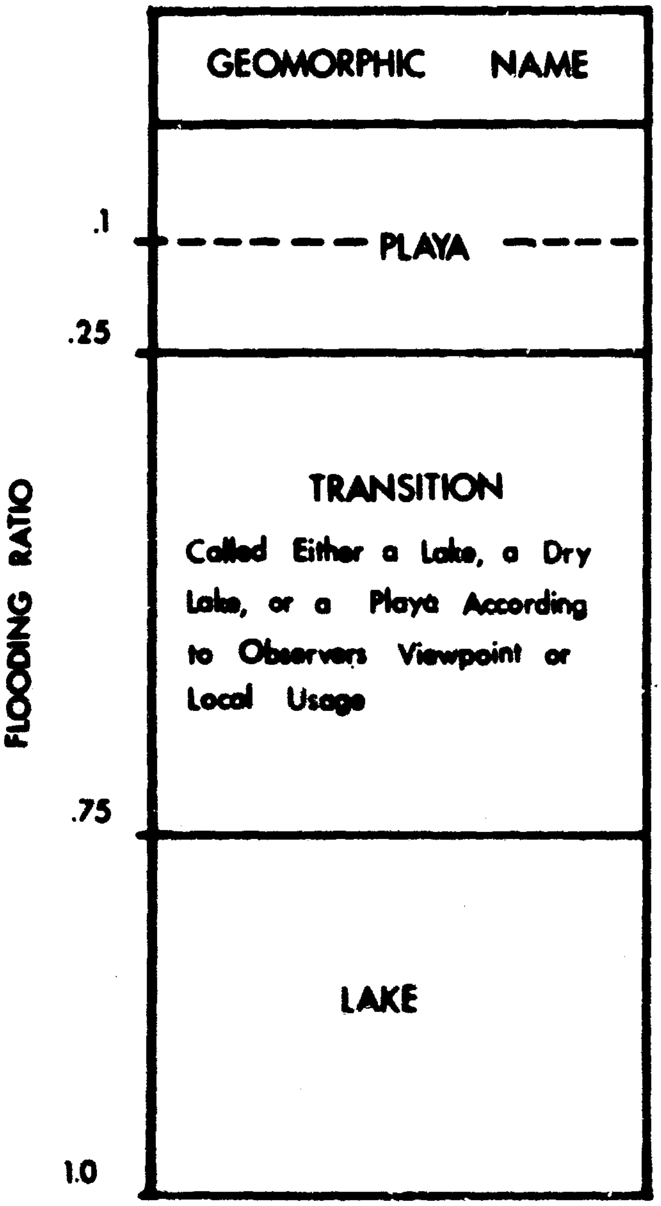

Table 2. Suggested oretical differentiation between lake and playa on basis of flooding ratio.

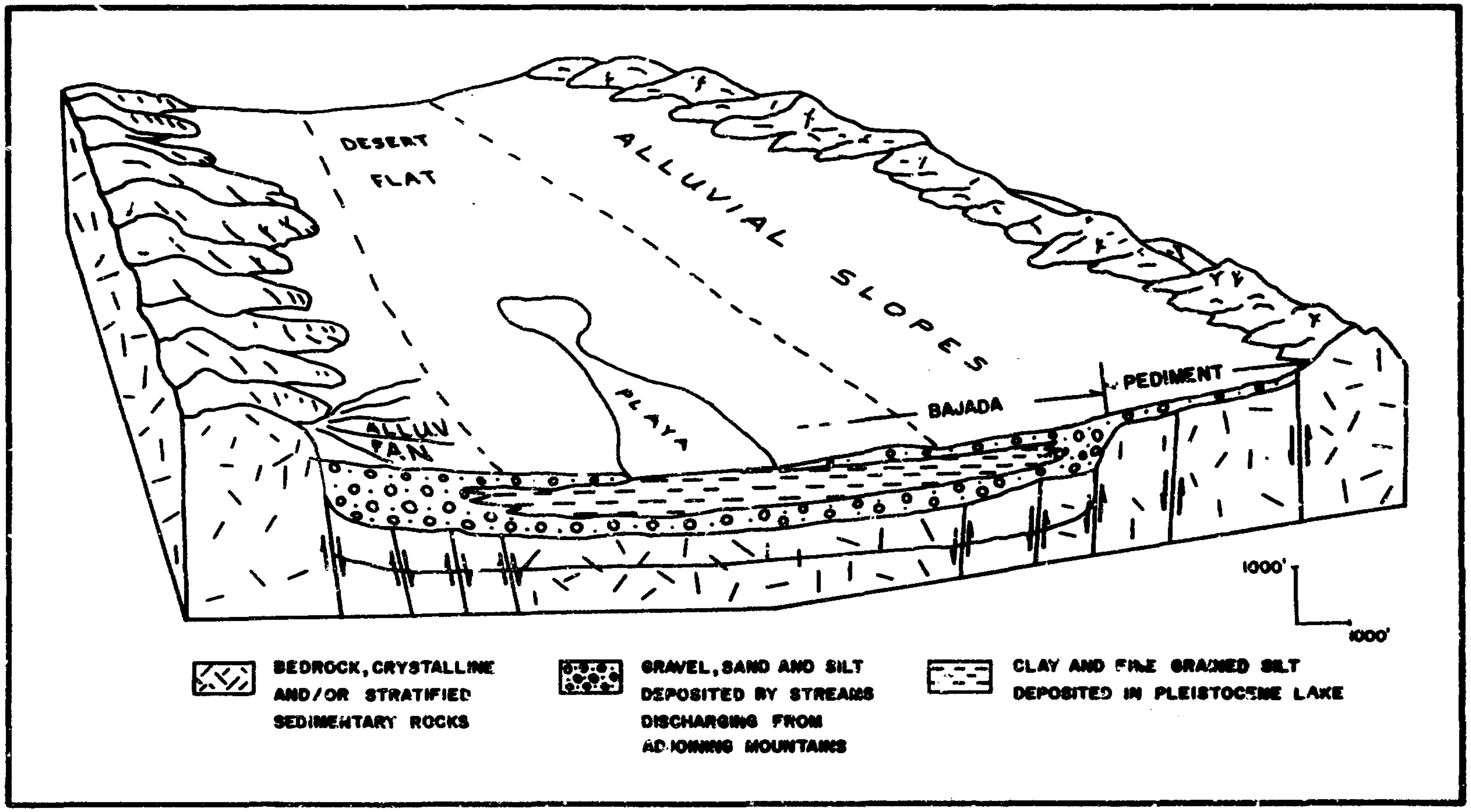

Figure 2. Block diagram showing geomorphic setting and sedimentary framework of idealized fine-grained playa studied in this investigation.

areas of bedrock or extensive sand dunes in complex configurations not considered in this generalized discussion. More complete descriptions of desert geomorphic features may be found in the references listed in "Previous Investigations".

Because they occupy the lowest parts of desert valleys, playas are commonly areas of ground-water discharge. Most recharge occurs through stream channels that cross the alluvial slopes and desert flats (Fig. 2) and a part of the recharge occurs directly from bedrock into alluvium of the desert valleys. A playa is a terminal discharging area if the potentiometric divide for a given aquifer encloses the playa resulting in total ground-water discharge occurring within the playa area. Potentiometric divides of some aquifers enclose two or more playas which may result in a "bypass playa" where part of the water discharges within the playa area and part moves down gradient to discharge at lower topographic elevations, or a playa situated too far above the potentiometric surface for ground water to discharge at its surface. Discharge of ground water in the playa areas occurs in three ways: (1) directly through the playa surface by capillarity from shallow aquifers or by artesian movement from deeper aquifers, (2) from springs which commonly occur near the gradations from coarse-grained bajada sediments to fine grained playa sediments (Fig. 2), and (3) from evapotranspiration by plants. The nature and amount of ground-water discharge is an important factor in determining playa surface morphology. For additional material on the general control of ground-water discharge through playa areas, the reader is referred to Motts (1965) and to Snyder (1962).

Major Playa Types Described in this Publication

This investigation shows that most playas in western United States can be divided into two basic types, "fine-grained playas" and "coarse-grained playas", each of which has a characteristic lithology and a distinctive surface type. By an increase of evaporites, coarse-grained playas become "crystal-body playas" which are important economically but rare in number and are not discussed in this publication.

The division of playas into coarse- and fine-grained types is based on the gross texture of playa sediments and differs from former classifications based on the microrelief or the lithology of sediments within a few feet of the playa surface. The gross or overall texture of playa sediments is a primary control on hydrologic processes which in turn control the formation and stability of surface types. This differentiation of playas by gross characteristics was determined by extensive drilling and detailed studies; therefore, it is not a practical classification for reconnaissance field work. For readily usable classifications of playa surfaces the reader is referred to Stone (1956), Neal (1965a), and Langer and Kerr (1966).

Coarse-grained playas are underlain by sediments of sand and silt size. The playas generally contain a shallow zone of saturation and a water table that is approximately coexistent with the playa surface. Discharge of ground water occurs by rapid capillary discharge and by direct evaporation from the water table. The coarse-grained playas are few in number and they have an entirely different surface morphology and a more diverse microrelief than the fine-grained playas. In contrast to the more slowly evolving surfaces of fine-grained playas, surfaces of coarse-grained playas change rapidly (frequently from week to week and month to month). Troy and Clayton are coarse-grained playas discussed in this publication.

Fine-grained playas are underlain by sediments from medium silt through fine clay deposited for the most part in extensive lakes that existed during the humid stages of Pleistocene time. Fine-grained playas do not contain a shallow zone of saturation or a water table because of the very fine-grained nature of their sediments. Typically the sediments interfinger with and are underlain by coarse-grained alluvium of bajadas and alluvial fans which commonly contain water under artesian conditions. Where high potentiometric surfaces occur above the playa surfaces, water moves upward through poorly permeable sediments by slow artesian movement and by capillarity. Rogers Playa, Rosamond Playa, Coyote Playa, and Big Smoky Playa are fine-grained playas discussed in this publication.

Playa Complexes Studied in this Publication

Playas occur singly and in groups or clusters called herein "playa complexes." A playa complex consists of two or more nearby playas related genetically for geological or hydrological reasons. Three playa complexes are discussed in this publication: the Barstow playa complex, the Tonopah playa complex, and the Edwards playa complex.

Coyote Playa and Troy Playa of the Barstow playa complex are "bypass" playas because some ground water flows through the sediments underlying both playas to discharge into the Mojave River (Figs. 3 and 4). Coyote Playa is a fine-grained playa underlain by a deep artesian aquifer and characterized by a small amount of ground-water discharge, whereas Troy Playa is a coarse-grained playa characterized by large amounts of ground-water discharge from a shallow water table. To a large extent, Troy Playa and Coyote Playa owe their geomorphic and hydrologic characteristics to differences in average

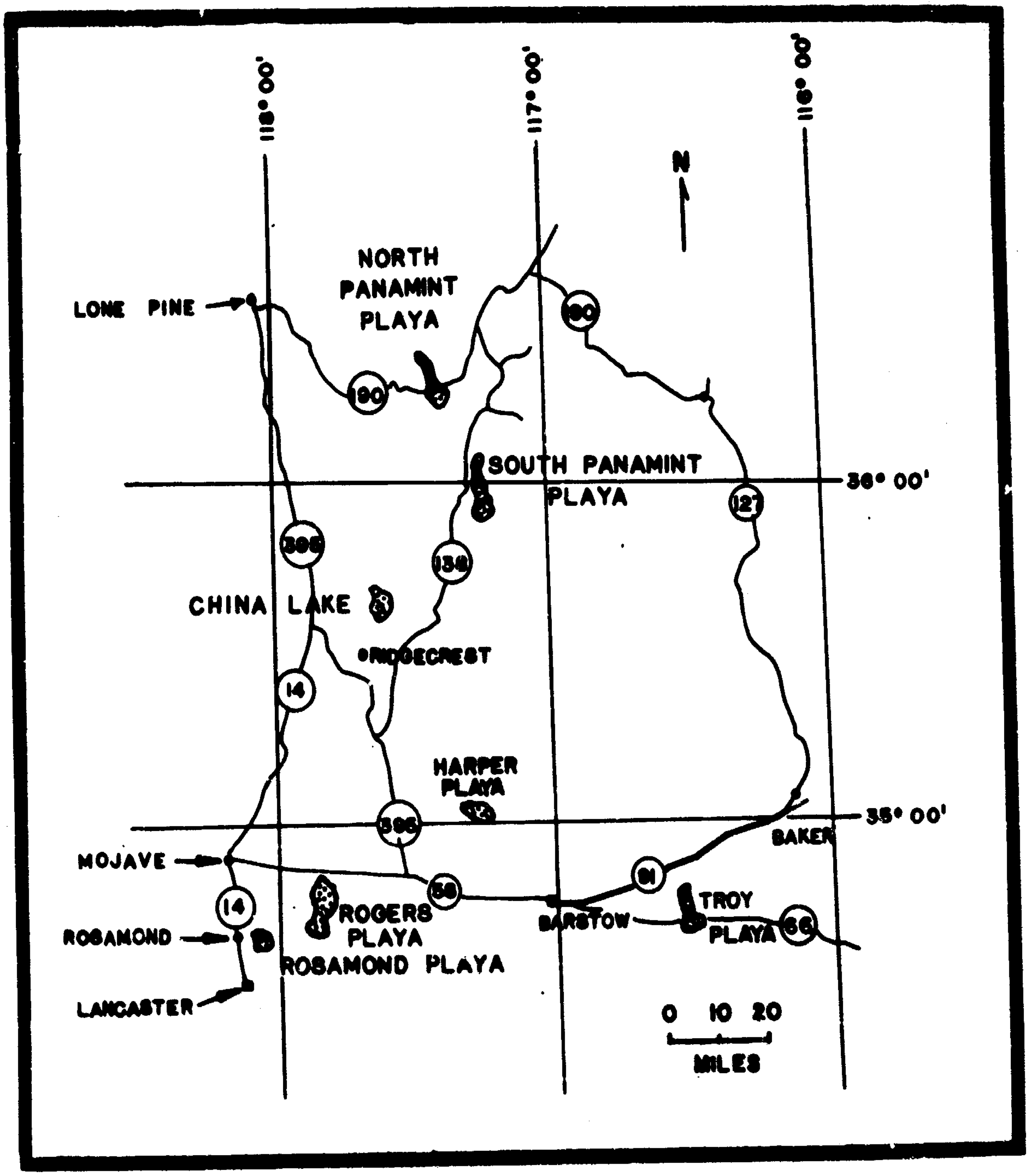

Figure 3. Playas of the Mojave Desert studied in this investigation.

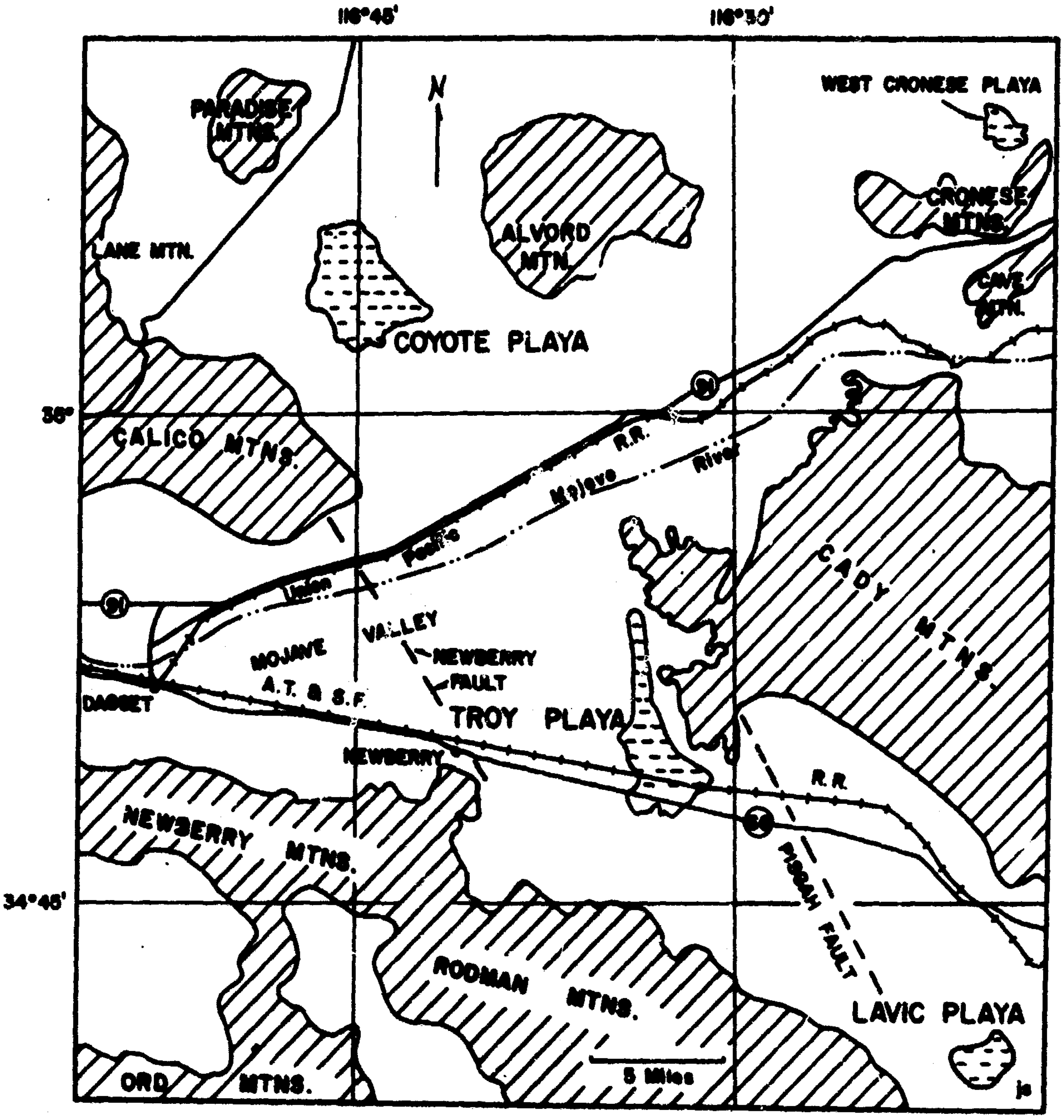

Figure 4. Location map of Coyote Playa and Troy Playa of the Barstow playa complex.

grain size of sediments underlying the playas. The difference in average size of sediments at Coyote (clay size) and Troy (silt size) appears to relate to different depositional environments in ancient Lake Manix. The Troy sediments were deposited along the periphery of the lake near entering streams, whereas the Coyote sediments were laid down in a deep embayment where very fine-grained sediments settled out (also see Chapters 3 and 5).

The Tonopah playa complex consists of several playas including Big Smoky and Clayton Playas, the two discussed in this publication (Fig. 5). Clayton Playa is a coarse-grained playa underlain by silt, sand, and evaporites; Big Smoky Playa is a fine-grained playa underlain by fine-grained silt and clay. The hydrologic and sedimentary differences between Big Smoky Playa and Clayton Playa are the result of several factors. One important factor is that Clayton Playa is the terminal discharging area for ground water draining a considerable portion of the Tonopah area; whereas Big Smoky Playa at a higher elevation, is a hydrologic bypass playa which discharges small amounts of ground water. Sediments of Clayton Playa are disturbed and chaotic because ground-water discharge is accompanied by deposition of large amounts of evaporites. On the other hand the fine-grained sediments of Big Smoky Playa were deposited in an ancient Pleistocene lake and are little disturbed by the relatively small amounts of salts deposited from little ground-water discharge.

The Edwards playa complex consists of Rogers Playa, Rosamond Playa, and Buckhorn Playa, all of which are underlain by sediments deposited in Pleistocene Lake Thompson. Although all three playas are underlain by silt and clay, the deposits underlying Rosamond are the finest-grained with fewer sand lenses because Rosamond Playa is located near the center of ancient Lake Thompson.

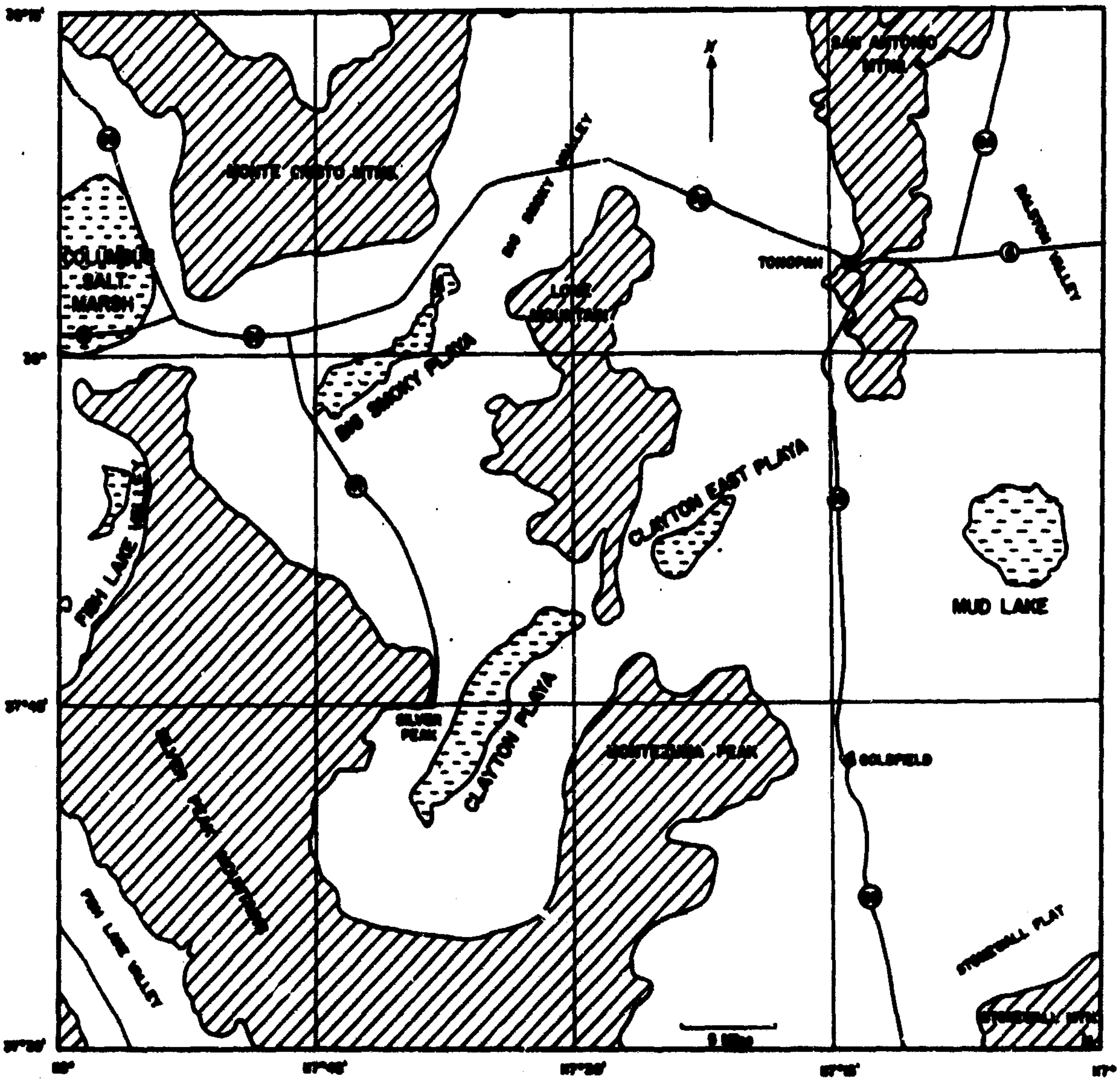

Figure 5. Location map of Clayton Playa and Big Smoky Playa of the Tonopah playa complex.

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CHAPTER 2: GEOLOGY AND HYDROLOGY OF ROGERS PLAYA AND ROSAMOND PLAYA, CALIFORNIA

Ward S. Motts[1]

David Carpenter[2]

ABSTRACT

From 1964 to 1968 five major playa-surface types were observed on Rogers Playa and Rosamond Playa: (1) a surface of "mud curls" or fragments of concave-upward mud polygons that sheared from the underlying surface, (2) a smooth, hard, compact surface, (3) an irregular puffy surface with higher porosity than the smooth surface, (4) a transitional surface containing areas of both the smooth and the puffy surfaces, and (5) a generally smooth surface characterized by a white crust of salt and carbonate. The surface types changed from year to year primarily because of surface-water floodings. The floodings were accompanied by the deposition of a thin sedimentation unit which upon drying formed mud curls, subject to wind deflation. The curls were characterized by a basal sand and silt grading upward into clay. Alternate freezing and thawing of the playa lakes produced rosette impressions on the playa surfaces and have been effective in shattering the surfaces.

The fine-grained silt and clay of Rogers and Rosamond Playas form a relatively thin "blanket" which rests on a much thicker deposit of sand and gravel. The blanket thickens from about 45 feet in the north part of Rogers and 75 feet in the south part to more than 200 feet in Rosamond Playa. This overall thickening of the brown, fine-grained blanket to the south and west is accompanied by a concomitant thickening of blue and gray silts and clays within the blanket. The blue and gray materials were probably deposited in a relatively deep-water reducing environment, whereas the brown materials were deposited in a shallow-water oxidizing environment.

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[1]Geology Department, University of Massachusetts, Amherst, Massachusetts

[2]Geologist, Mobil Oil Company, Shreveport, Louisiana

Water under hydrostatic pressure was encountered when test holes penetrated sand and gravel deposits underlying the fine-grained silt and clay blanket. On both playas a depressed potentiometric surface extended along the sedimentary axis of thickest clays and silts. Soil moisture contents of samples from test holes showed (1) a general downward increase of moisture in fine-grained sediments of the same size, (2) a decrease of moisture content where the sediments became more silty and sandy, and (3) a decrease of moisture in some clays and silts resting above sand zones. Throughout the northern part of Rogers Playa, the potentiometric surface has lowered within a sand and gravel body resulting in capillarity and gravity drainage from the overlying fine-grained silts and clays. Increasing desiccation of the fine-grained deposits accompanied by the lowering of potentiometric levels has been an important factor in the continued formation of giant desiccation polygons on Rogers Playa. Fewer giant desiccation polygons have formed on Rosamond Playa except along the inner playa margin where sand and gravel interfinger laterally with the silt and clay blanket. The higher potentiometric levels within the thick silt and clay deposits have resulted in less capillarity and gravity drainage at Rosamond Playa.

INTRODUCTION AND ACKNOWLEDGMENTS

Rosamond Playa and Rogers Playa were investigated by the authors from 1964 to 1968 (Fig. 1, Chap. 1). Rogers Playa occupies an area of about 46 square miles, lies within the boundaries of Edwards Air Force Base, and is used at frequent intervals for aircraft landings. The playa is impassable to vehicle traffic when wet; however, when dry, its surface is extremely hard and competent and the crust has the necessary bearing strength to support large aircraft. Rosamond Playa occupies the farthest westward position of the Mojave Desert playas and is seldom used for aircraft landings, but is used frequently as a site for desert research. In the fall and winter months Rogers and Rosamond Playas receive the most rainfall which often produces flooding to depths of several inches (Fig. 1). For detailed information on the climate of the Rogers-Rosamond area, the reader is referred to Dutcher and Worts (1963, p. 23).

During the summers of 1965 and 1966 a drilling program was conducted on both playas to study the sedimentology and hydrology of playa sediments and the origin of giant desiccation polygons. Some of the results of the program are discussed in Motts and Carpenter (1968). Cores and sediment samples were taken in 3 test holes from Rosamond Playa and in 14 test holes from Rogers Playa; depths of the test holes ranged from 30 to 275 feet. Water samples were obtained and analyzed for chemical constituents by the Water Resources Division of the U. S. Geological Survey, Sacramento, California. Cores from the test holes were logged in the field and samples for soil moisture analyses were collected at 5 to 10 foot intervals for gravimetric analyses made at the sedimentation laboratory of the University of

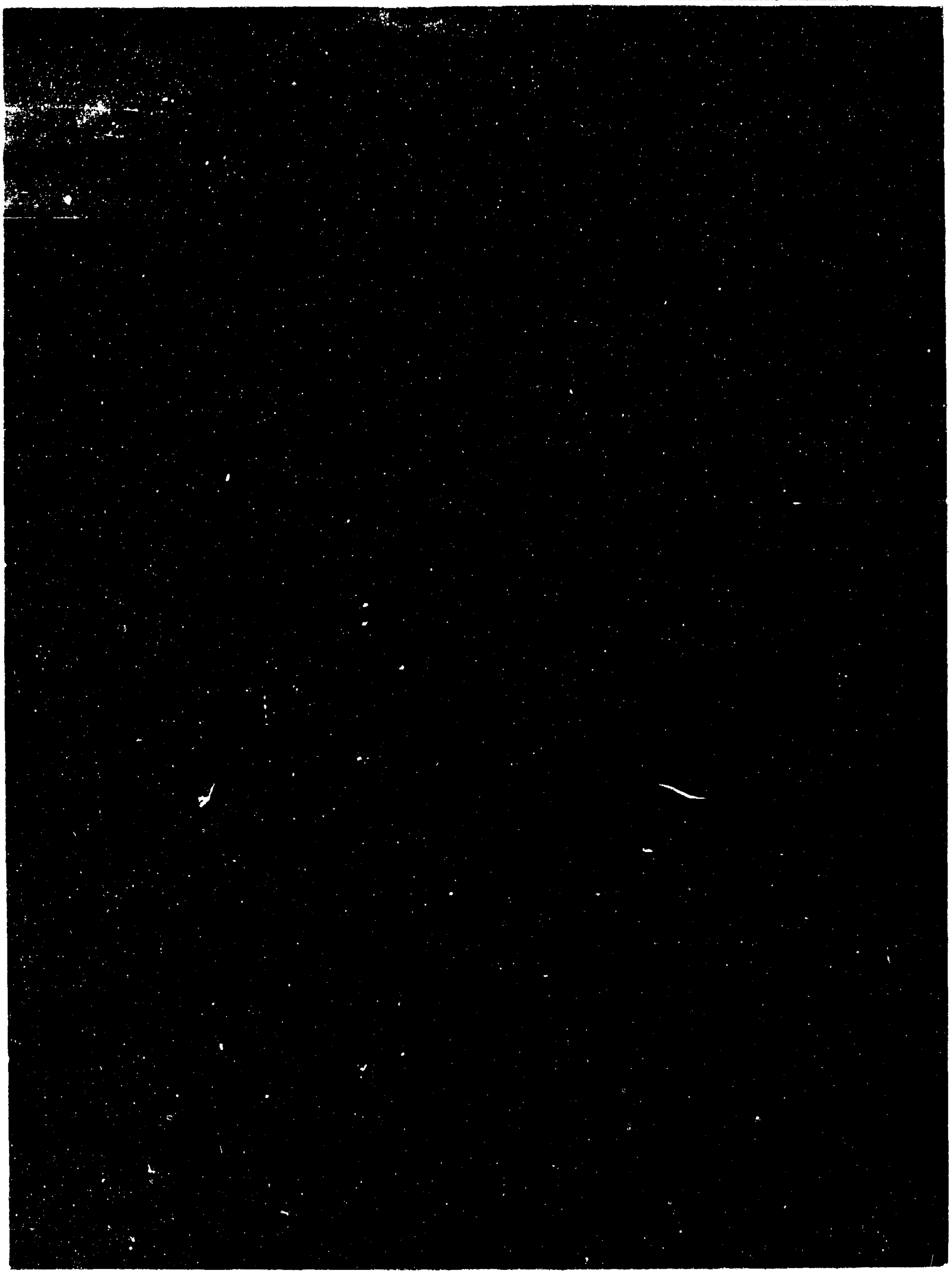


Figure 1. Flood water moving across the surface of Rogers Playa from action of wind. This shifting of water plays an important role in playa-surface morthology. (See also Chap. 7 of this publication.)

Massachusetts. David Drake assisted on the drilling program and Tom Lyman performed detailed size and mineralogical analyses of the test cores at the University of Massachusetts. The authors are indebted to many people at Edwards Air Force Base, especially Mr. Joseph Reif whose cooperation helped make this study possible. The authors would also like to thank hydrologists of the U. S. Geological Survey, including L. S. Dutcher, F. W. Giessner, and W. R. Moyle, Jr. for their interest and cooperation in this project.

Geologic and Geomorphic Setting

Rogers Playa and Rosamond Playa are part of Antelope Valley which is a large topographic and ground-water basin bounded on the north and northwest by the Tehachapi Mountains, on the south and southeast by the San Gabriel Mountains, and on the east by low hills and divides that separate the basin from Lower Mojave Valley, Harper Valley, and Fremont Valley. Antelope Valley is underlain by rock units of three major groups which are separated by unconformities (Dibble, 1963, p. 141): (1) pre-Tertiary crystalline rocks, (2) Tertiary volcanic pyroclastic and sedimentary rocks, and (3) Quaternary sedimentary deposits (Fig. 2). The total thickness of the Tertiary and Quaternary rocks is very great. Maybey (1960) states that the depth to basement rock under Rosamond Playa is about 10,000 feet.

The Quaternary sedimentary deposits which are of primary interest to this study consist of clastic materials ranging in size from large boulders on the alluvial fans to fine-grained clay in the playa. For the most part, the deposits have been carried by streams draining the adjoining mountains, however, some have been carried by wind. The deposits were laid down in alluvial fans, along stream channels and flood plains, and in lakes formed

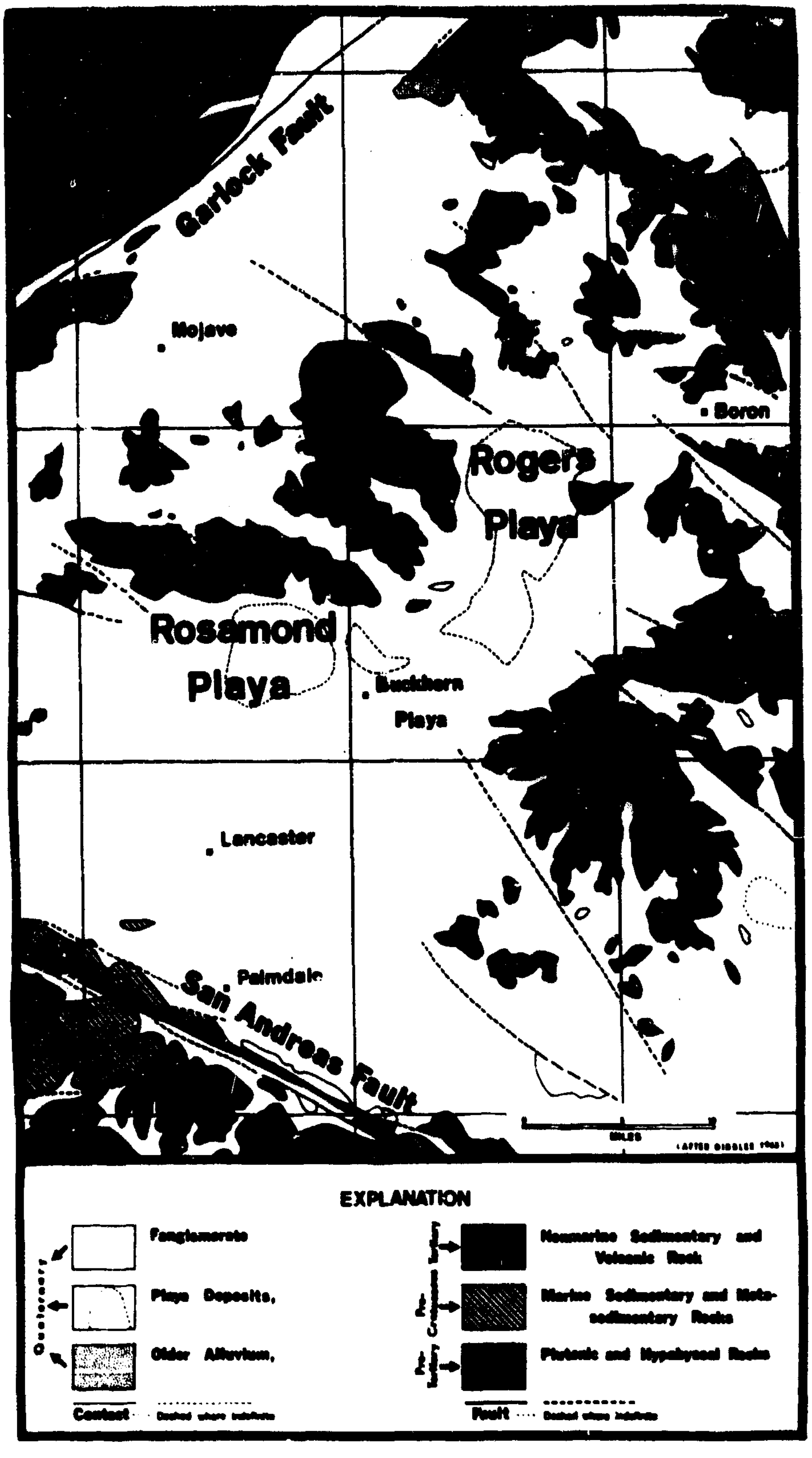


Figure 2. General geology and structure of Antelope Valley (after Diblee 1963).

in pluvial times. The Quaternary sedimentary deposits have been subdivided into Older Alluvium and Younger Alluvium. Older Alluvium, which had been deformed and dissected in places, ranges in thickness from a few feet to more than 1500 feet (Dutcher and Worts, 1963, p. 77). Parts of the Older Alluvium are cemented into a firm fanglomerate. Younger Alluvium consists mostly of unconsolidated gravel, sand, silt, and clay which form recent fan and alluvial deposits, playa and lake deposits, and lake-shore deposits. Fine-grained playa and lake deposits underlie Rogers and Rosamond Playas and grade laterally into equivalent coarser lake-shore deposits. In the following discussion the term playa deposits will be used for those sediments that underlie the playas and include materials of playa and lake origin. Both Rosamond and Rogers Playas are underlain predominantly by the fine-grained deposits of ancient Lake Thompson which occupied most of Antelope Valley in Pleistocene time. Geological evidence of the extent of Lake Thompson includes the shorelines which are exposed at higher elevation than the playa deposits.

The shape of Rogers and Rosamond Playas is controlled in part by faults. The borders of Rogers Playa approximately parallel major faults and Rosamond Playa is bordered on the north by a ridge of fault origin. Both playas are situated in the western part of the Mojave block, a major structural feature bounded on the north by the Garlock fault and on the south by the San Andreas fault (Fig. 2).

SURFACE TYPES OF ROGERS AND ROSAMOND PLAYAS

Rogers and Rosamond Playas for the most part have hard compact surfaces and Stone (1956, p. 68, 70) classified Rogers Playa as the type example of the hard clay-pan class of playas. Rogers Playa and Rosamond Playa have numerous variations of this basic surface type that change from one year to another as shown in studies by Neal in 1962-63, by Carpenter in 1965-66, and by Motts in 1967-68.

Surface Types in 1962-63

Neal (1963) noted the following surface types on Rosamond Playa: (1) concave-upward polygons or, as Neal called them, clay saucers--these are the "mud curls" of this report, (2) a flat clay surface along the playa periphery characterized by desiccation polygons as much as two feet across, (3) areas with a relatively hard surface containing small polygons from 1/8 to 1/2 inch across, (4) areas of a convex type of polygon 1/2 to 1-1/2 inches across (called "cobblestone" pavement by Neal), (5) a hard dry surface containing slightly raised polygons ranging from 1 inch to 1-1/2 feet across. Neal noted most of the above types were also present on Rogers Playa as well as a hard compact surface which he described as "billiard table" in appearance. The extremely smooth billiard-table surface, extensive on the western side of the playa in 1963, was characterized by two or more generations of mud cracks and by darker stains resulting from standing water. Neal believed that the billiard-table surface contained more silt than other areas of the playa surface. The cobblestone type of surface was also common on Rogers Playa in 1962-63.

Surface Types in 1965-66

Carpenter mapped the surface of Rogers and Rosamond Playas in 1965 and 1966 and noted four major surface types: (1) a smooth-hard surface, (2) a puffy surface, (3) a transitional surface, and (4) a surface of concave-upward polygons or "mud curls" which may be further subdivided into polygonal shreads a few millimeters thick and mud saucers which range up to several centimeters thick. Each of these four surface types changed in areal extent from summer 1965 to summer 1966 as shown in Figures 3-6.

The smooth-hard surface (probably in part the "billiard-table" surface of Neal) was typically pale buff to pale red in color, very dry and brittle, and had little or no microrelief other than some areas of rougher ground (Fig. 7). Carpenter, like Neal, noted that the smooth-hard surface was generally more silty than other surfaces; however, Carpenter observed that the higher silt content occurred mostly at the surface and did not continue with depth. Small desiccation polygons, occurring on the smooth-hard surface were generally about six inches across. A car travelling across the surface left only a slight impression.

The puffy surface of Rogers and Rosamond Playas was typically pale red to light buff in color, very dry and brittle; the irregular character of the surface rarely exceeded two centimeters in height (Fig. 8). The puffy surface commonly had one or more generations of small desiccation polygons. A car crossing the surface left a clear impression. The sediments beneath the puffy surface were more porous and friable than beneath the other surfaces, probably because of the numerous small desiccation polygons that have been subject to erosion by flooding and sheet wash (Fig. 9). The irregular surface may also result from processes associated with formation of mud curls produced by the interaction of surface water with playa clays.

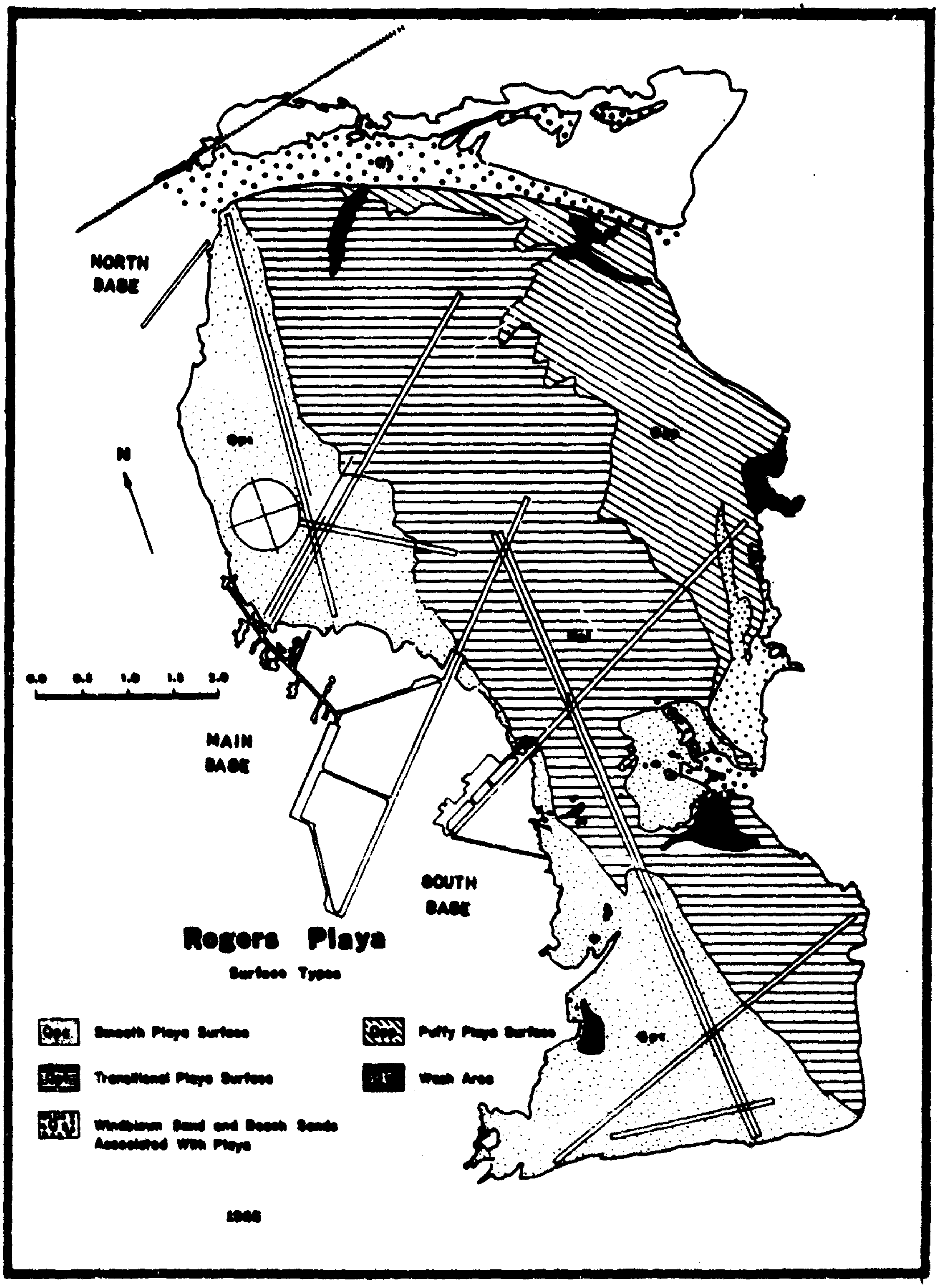


Figure 3. Playa surface types on Rogers Playa 1965. (Mapped by David Carpenter).

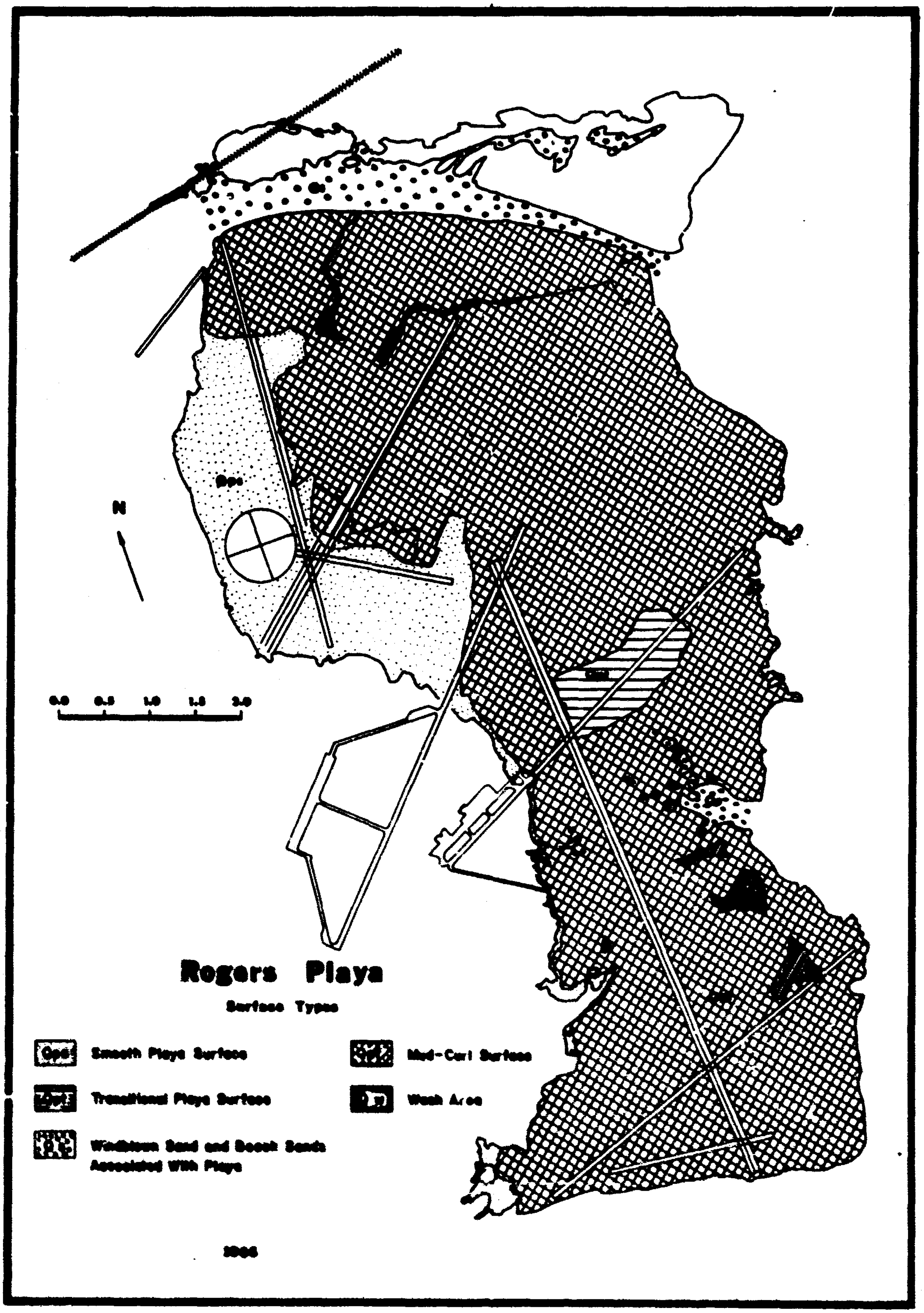


Figure 4. Playa surface types on Rogers Playa 1966 (Mapped by David Carpenter).

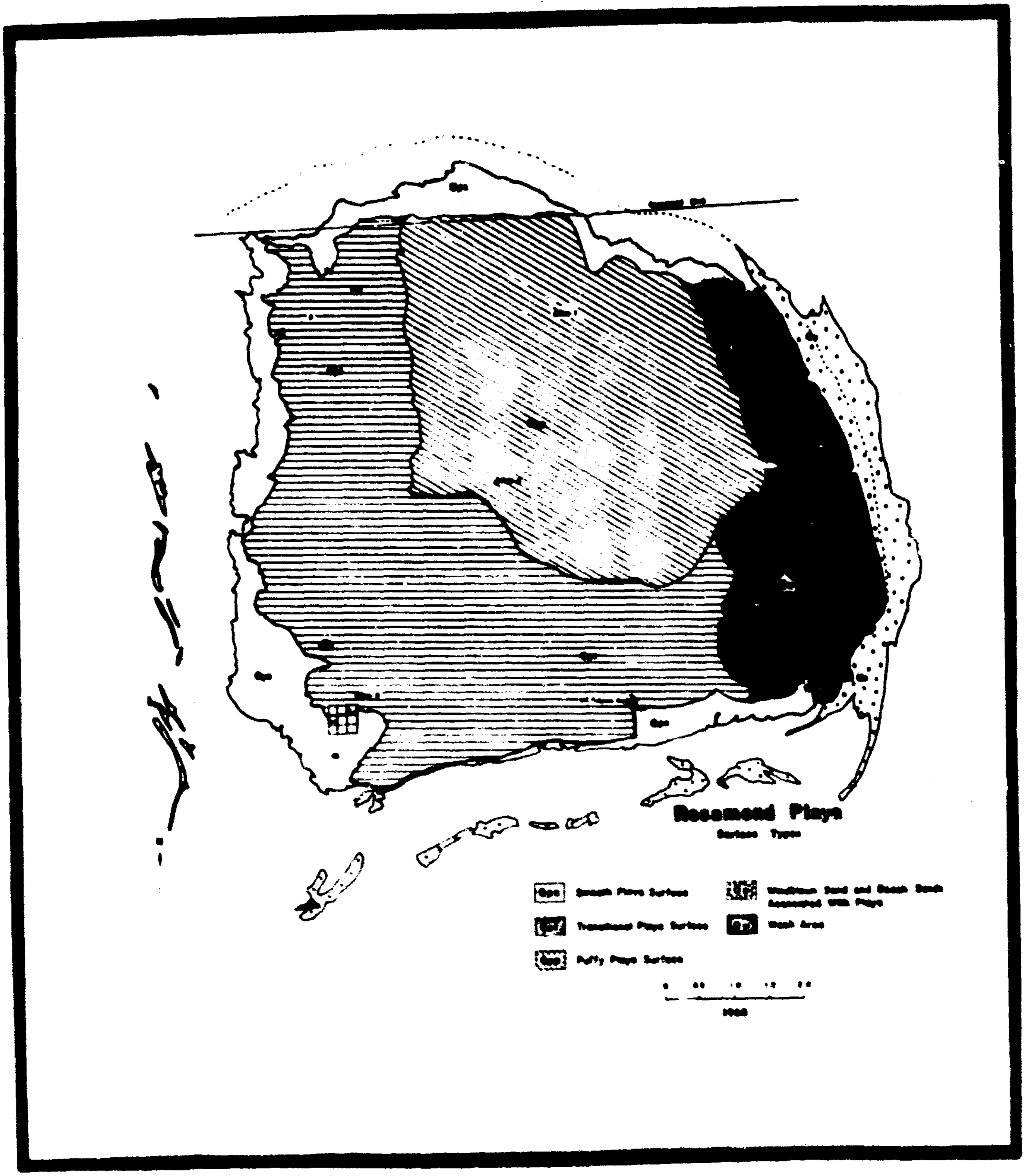


Figure [illegible]. Playa surface types on Rosamond Playa [illegible]. (Mapped by David Carpenter.)

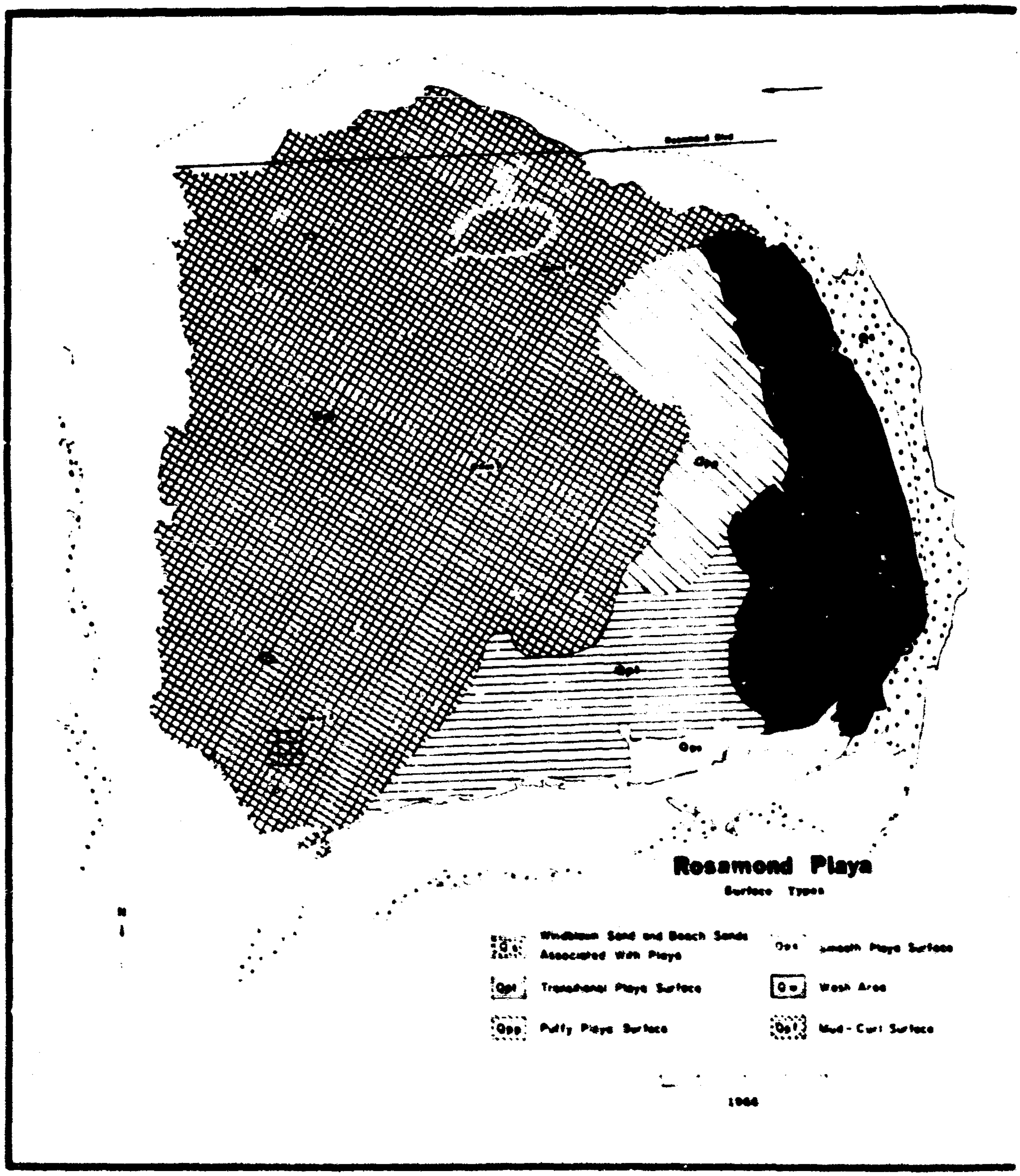


Figure 6. Playa surface types on Rosamond Playa in 1966. (Mapped by David Carpenter.)

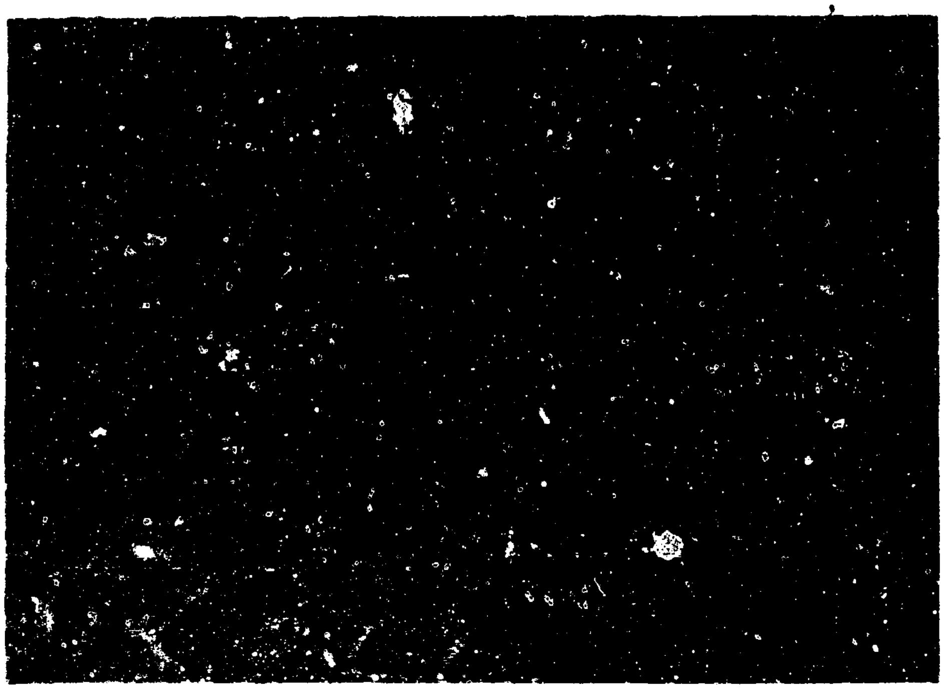


Figure 7. Smooth, hard surface on Rogers Playa, 1968.

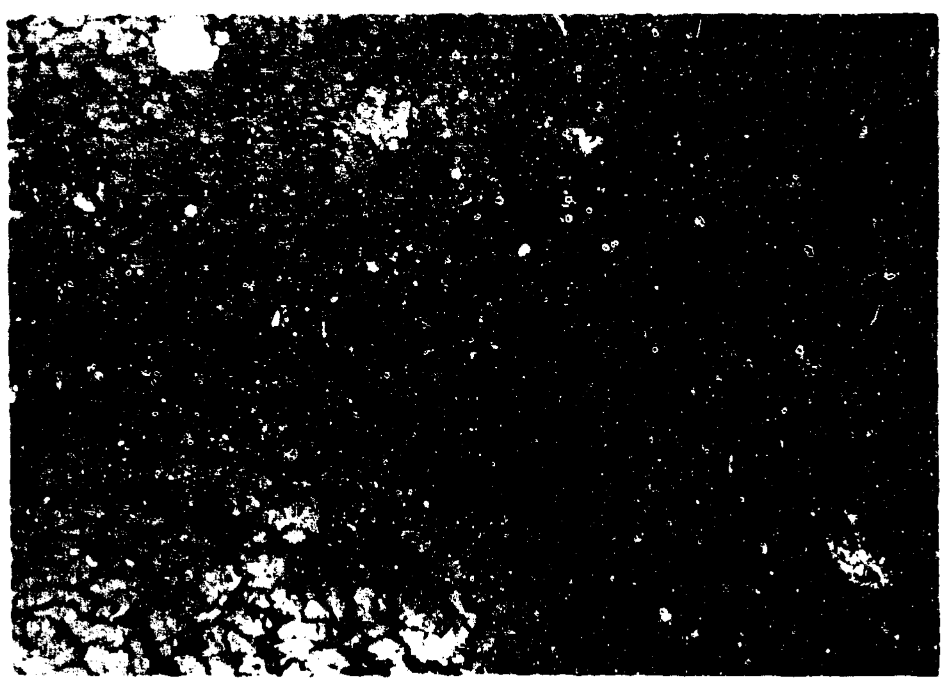


Figure 8. Typical "puffy" surface on Rosamond Playa, 1965.

Figure 9. Photograph showing typical nature of friable sediments underlying puffy surface on Rosamond Playa, 1965.

Figure 10. Flakey (mud-curl) surface on Rogers Playa, 1966.

In this report puffy surface is used as a descriptive term relative to other surfaces of Rogers and Rosamond Playas and is different morphologically than the puffy surfaces of most other coarse-grained and many other fine-grained playas. Puffy surfaces of the latter playas are highly irregular, many having been formed by ground-water discharge accompanied by disrupting effects of salt deposition in surficial playa sediments. "Puffy" is a useful descriptive term for surfaces of a specific playa. However, one should be cautions in making generalizations of all puffy surfaces from a study of a few because of the wide range of morphologic and genetic types included under this term.

The transition surface of Rogers and Rosamond Playas was typically pale red to light buff in color, very dry, brittle, and it varied between the puffy surface and the smooth-hard surface described above. The transitional surface consisted of isolated areas of the smooth surface to 100 feet across or the puffy surface surrounded by the other dominant surface types.

The surface of mud curls on Rogers and Rosamond Playas was typically pale red in color, very dry and brittle; microrelief on the surface resulted from fragments of polygonal mud curls. The curls ranged in size from one inch to twelve inches across (Fig. 10). Carpenter noted that in 1966 most of the curls less than 1/2 inch thick were concave upward. Many of the curls were characterized by a basal layer of silt. Laboratory analyses indicate that the upper part of the curls have a greater clay content than either the basal part of the same curl and/or the uppermost sediments of the playa. The mud curls were thickest in depressions, washes, and subsidence areas around vegetation. After they dried, the curls were commonly harder than

the older surface especially if the latter surface was puffy. A car traveling over the mud-curl surface left a subdued impression of broken platelets (Fig. 11).

The surfaces of Rogers and Rosamond Playas in 1965 generally ranged from a smooth-hard surface in the north, west, and southwest, to a puffy surface in the east. On Rosamond Playa, the smooth-hard surface extended for about a half mile from the western and northern playa boundaries before grading into a transitional surface which in turn graded into a relatively soft puffy surface extending to the eastern boundary of the playa (Fig. 5). On Rogers Playa, the smooth-hard surface, extending 3 miles eastward in the southern portion of the playa and 2 miles eastward in the northern portion, graded into a hard puffy surface which continued to the eastern boundary of the playa (Fig. 3).

The surfaces of Rogers and Rosamond Playas were completely changed from the summer of 1965 to the summer of 1966. Modification of the playa surfaces was due to the effects of water which stood on the playas for 5 months during the winter of 1965-66. On Rosamond Playa a new mud-curl surface in 1966 completely covered the older smooth-hard surface on the west and north and covered most of the puffy and transitional surfaces on the east (Fig. 6). A puffy surface was still present on the eastern part of Rosamond Playa in 1966 but it was harder than it was in the summer of 1965. Hardening of the puffy surface was probably due to surface water consolidating the porous and fractured silt and clay. Most of Rogers Playa was also covered with a mud-curl surface except in the western part which retained a smooth-hard surface in some areas which apparently were not covered with water during the winter of 1965-66. Gradation from the smooth surface on the west to the

Figure 11. Impressions left by vehicles traveling over mud-curl surface, Rogers Playa, 1966.

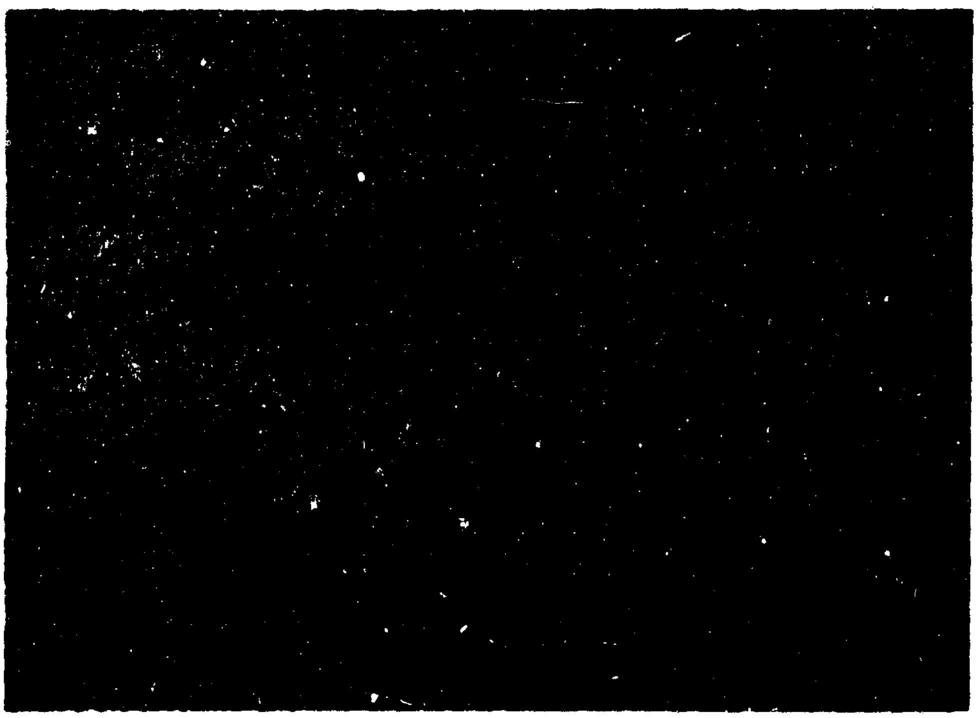


Figure 12. Rosette pattern caused by ice-crystal formation in northwestern part of Rogers Playa, 1968.

puffy surface on the east was modified on both Rogers and Rosamond Playas by obstructions such as plant mounds and playa "islands"; the surfaces around the obstructions tended to be much smoother than the adjacent surfaces. Broad drainage areas on the playa tended to be darker than the adjacent surfaces, varied in type from mud curl to puffy, and were commonly characterized by numerous polygonal cracks. Travel by car across areas in the eastern part of Rosamond Playa was difficult in 1965 because of puffy irregular ground but easier in 1966 because of smoother harder ground.

Surface Types in 1967-68

Motts visited Rosamond Playa on November 19, the first day of a blanket rain which flooded many playas in the Mojave Desert including Rosamond, Rogers, Coyote, Troy and North Panamint. During the rainstorm on Rosamond Playa isolated pools of water formed that ranged from 4 feet to more than 30 feet across; the water contained considerable amounts of clay in suspension. The playa surface was wet and slippery and many polygonal cracks were filled with water.

It is noteworthy that large areas of water remained on Rogers and Rosamond Playas until early spring 1968, whereas Coyote and North Panamint Playas were free of water three weeks after the November rainstorm. On the latter playas, water rapidly drained into the subsurface through numerous fracture openings of which many were associated with giant desiccation polygons. Further information on the rapid infiltration of water through the surface of Coyote Playa is presented in Chapter 3, Part 2.

Rogers Playa

By February 1968, some areas of Rogers Playa were free of water; however, several large areas of water were being pushed from one part of the playa to another by wind. In February the following playa features were noted on Rogers Playa: (1) "rosette" impression patterns, (2) "mud-curls" or concave polygons, (3) "cobblestone" or convex polygons, and (4) a white surface of a salt and carbonate crust. Most of these surface features belonged to the smooth-hard surface type described by Carpenter. The puffy surface was not present because shifting playa-lake water had probably reconsolidated the porous surface into a smooth-hard surface.

Rosette impression patterns were common throughout the northern part of Rogers Playa and were caused by ice crystals forming and pressing into the soft playa mud as the result of freezing of the playa lakes (Fig. 12). On Rogers and Rosamond Playas water commonly freezes solid during the night and thaws again during the day (Joseph Reif, personal communication). This alternate freezing and thawing may help shatter the playa surface and make it more susceptible to wind erosion, particularly where numerous polygonal cracks occur and ice can form within the cracks. Polygonal cracks were formed along the trend of the ice rosettes because the rosettes were a zone of weakness on the playa surface. Ice rosette patterns were present in several depressions and channels but not on the adjacent higher playa surfaces apparently because water was either present only in the depressions or water was deeper in the depressions.

In February mud curls were forming or had formed on many parts of Rogers Playa particularly in depressions and channels. At one locality in the northern part of the playa mud-curl cracks in the process of forma-

tion extended to depths of 1-1/2 inches into the playa surface. In a depression in the north central part of the playa, thin mud curls less than a fraction of an inch thick and larger curls (1/2 to 3/4 inches thick) had formed; the curls ranged from 3 to more than 12 inches across. Mud curls had also formed on the southern part of the playa where at one locality they averaged 1/8 to 1/16 of an inch thick, ranged from 1-1/2 to 9 inches across, and averaged from 4 to 7 inches across. Significantly thicker mud curls were beginning to form beneath the thinner ones.

"Cobblestone" or convex polygons occupied large areas and ranged from 1 to 4 inches across; microrelief on numerous polygons ranged from about 1/4 to 3/4 of an inch. Similar to mud curls, many cobblestone polygons formed in depressed areas where water was present for a long time. It is an interesting question how both cobblestone polygons and mud curls can form under these similar conditions.

Some areas of Rogers Playa had light-colored crusts containing salt and carbonate similar to crusts on Coyote and Troy Playas. The salt and carbonate crusts may have formed from material dissolved by flood water from other areas of the playa surface. In places, the white crust is a fraction of an inch thick, and it gives the entire playa a white uniform appearance. The redeposited carbonate material is granular and susceptible to wind erosion as indicated by a large amount of dust when cars crossed these areas.

There were areas on Rogers Playa where branching channels made elaborate erosional patterns called "desert flowers" (Fig. 13). In some places the dendritic patterns adjacent to their main channel cut as deep as 2 or 3 inches into the surface. Erosion by surface channels of this type may be one way that playas are eroded to lower base levels.

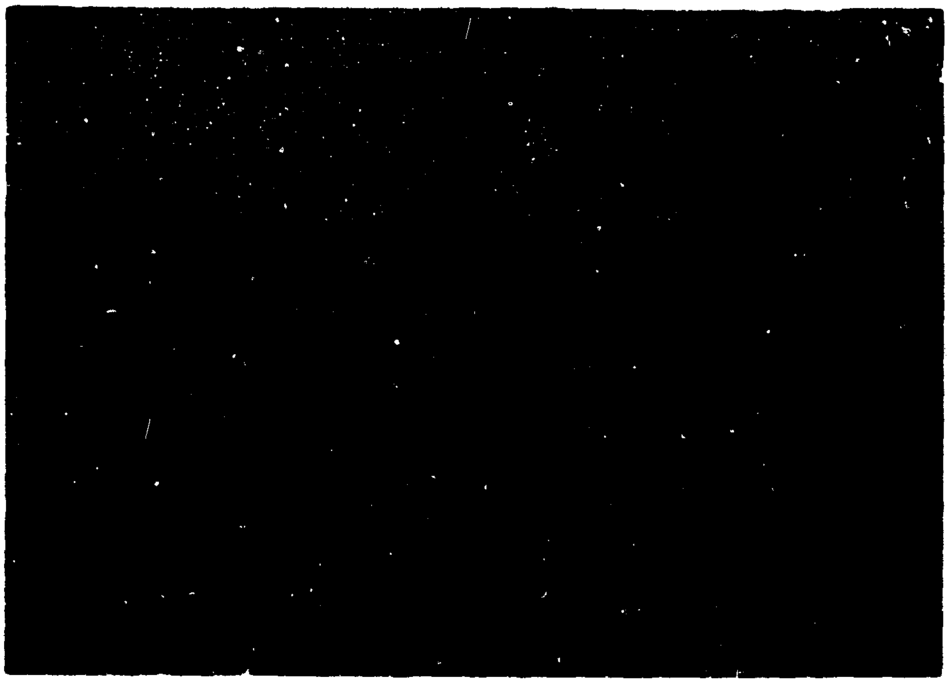


Figure 13. Surface erosion in northeastern part of Rogers Playa forming "desert flower", 1968.

Figure 14. Small channel in northern part of Rosamond Playa characterized by: (1) mud-curls in channel center, (2) convex-upward polygons on higher areas adjacent to channel, (3) halite and carbonate stain on surface adjacent to channels, and (4) parallel subsidence fractures on each side of channel.

Rosamond Playa

In February 1967 the surface types of Rosamond Playa were similar in many respects to those of Rogers Playa. They consisted of (1) mud curls or concave polygons, (2) "cobblestone" or convex polygons, (3) areas of white calcium carbonate crust, and (4) a wavy, undulating surface. Areas of puffy surface were not observed because shifting playa-lake water had probably compacted the porous surface and because much of the playa that contained puffy ground in 1965-66 could not be visited due to standing water.

Mud curls formed in depressions and channels on Rosamond Playa, as they had on Rogers Playa. In February 1968, the curls were beginning to form around the margin of the playa lake at Rosamond. As the water evaporated and the shore line retreated, mud curls formed in the newly dried areas. Mud curls were also present in shallow channels leading into the playa lake (Fig. 14). For example, in a channel 20 feet wide located on the southeast part of the playa, mud curls ranged in size from 1 to 7 inches across and averaged 3 to 6 inches across. The channel was a light brownish color. Each side of the channel had a white band (carbonate and/or halite) characterized by cobblestone polygons which averaged about 2 inches across; cracks of these polygons were about 1/8 inch across and had been enlarged by surface water erosion.

Mud curls were also found in mud flats surrounding small islands on the playa. Trees and other plants grew on some of the islands which appeared to be areas of subsidence, probably due to extensive evapotranspiration. Around depressed areas water was ponded in some places and in other places ice rosette patterns had formed.

A white surface of calcium carbonate similar to the one on Rogers was present on parts of Rosamond Playa. On this surface incipient cracks were forming into a large set of polygons ranging from about 1 to 4 feet across with a smaller set ranging from 1/2 to 3 inches across.

On the northwestern part of Rosamond Playa a surface type was observed that was not present on Rogers Playa--a wavy, undulating surface with micro-relief ranging from about 1/4 to 1/2 inch. This wavy surface resembled some surfaces on Coyote Playa; however, its microrelief was much less than most Coyote surfaces. The surface was broken by irregular "zig-zag" polygonal cracks through which capillary discharge of ground water occurred. These newly formed polygons ranged from about 1 to 2-1/2 feet across and had an average size of about 1 foot. These observations substantiated those of previous years that ground water was discharging from the western side of Rosamond Playa.

SEDIMENTOLOGY OF DEPOSITS UNDERLYING PLAYAS

Most fine-grained silt and clay underlying Rogers and Rosamond Playas was not deposited in recent playa lakes but in ancient Lake Thompson (see Chapter 7). These silt and clay deposits form a relatively thin blanket resting on a thick sequence of sand and gravel. Figures 16 to 22 locate and show stratigraphic sections of these fine-grained deposits which range in thickness from 0 to more than 200 feet in Rosamond Playa, from 0 to more than 75 feet in the south part of Rogers Playa, and from 0 to 45 feet in the north part of Rogers Playa. As shown in Figure 18, two areas of thick silt and clay underlie Rogers Playa; one in the southern and the other in the northern part of the playa. As shown in Figures 17 to 19, the fine-grained deposits of Rogers Playa also thicken along the geographic axis of the playa, which is generally parallel to section B-B'.

This overall thickening of the fine-grained blanket to the south and west is accompanied by a thickening of blue and gray silts and clays, and a concomitant thinning of similar-textured but brown deposits within the blanket (Figs. 23 and 24). The blue-gray materials may have been deposited under deep-water reducing conditions, and the brown materials deposited under shallow-water oxidizing conditions.

Deposits of the silt and clay fine-grained blanket may be subdivided into four predominant types: (1) an upper silty clay unit, (2) a lower highly plastic clay unit, (3) varve-like alternation of silt or sand and clay, and (4) lenses of silt and sand interlayered in the fine-grained playa materials. The upper silty clay unit is a maximum of 23 feet thick in the southern part and 18 feet thick in the northern part of Rogers Playa. The

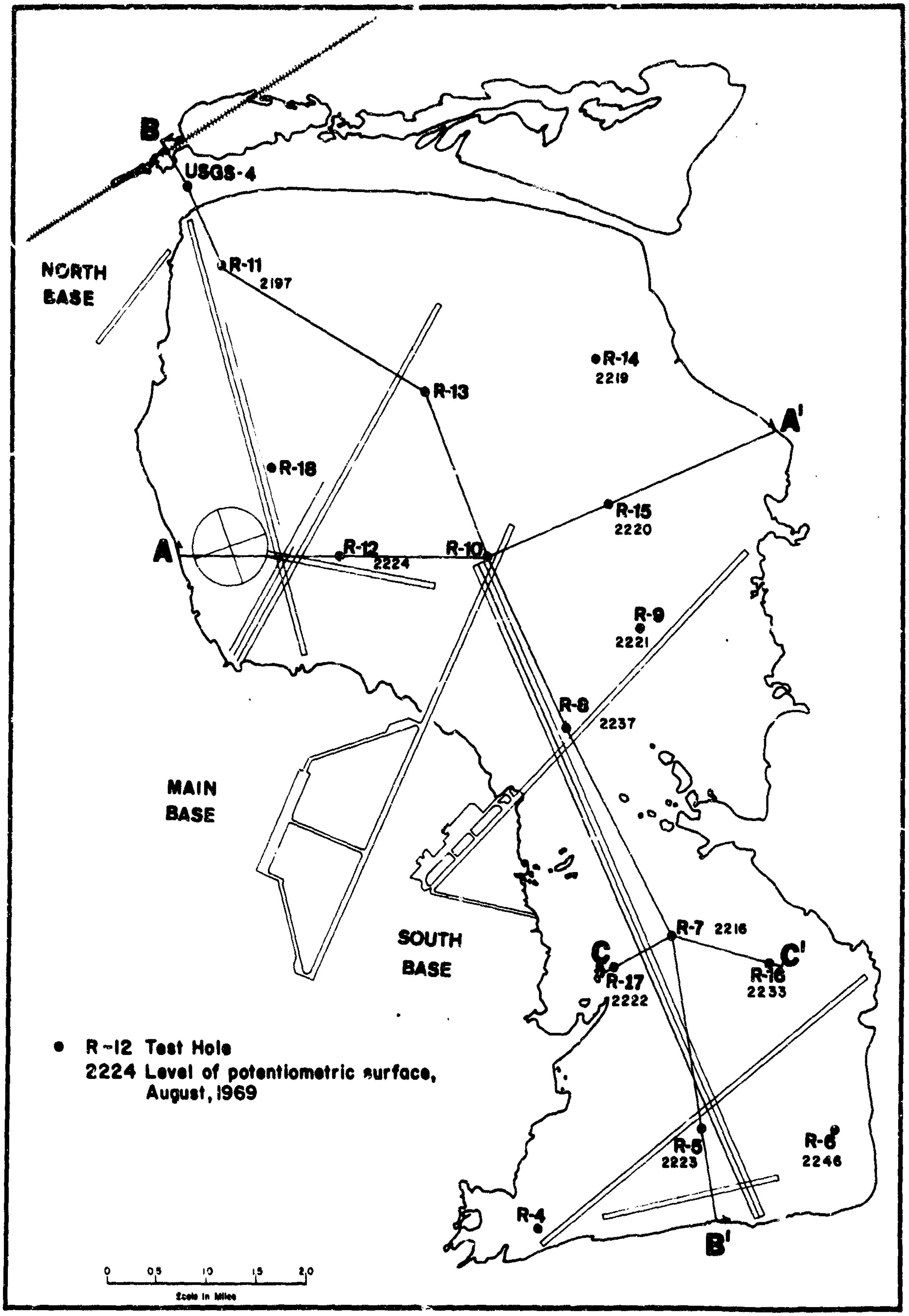


Figure 16. Map of Rogers Playa showing lines of cross sections and elevations of potentiometric surfaces in test wells.

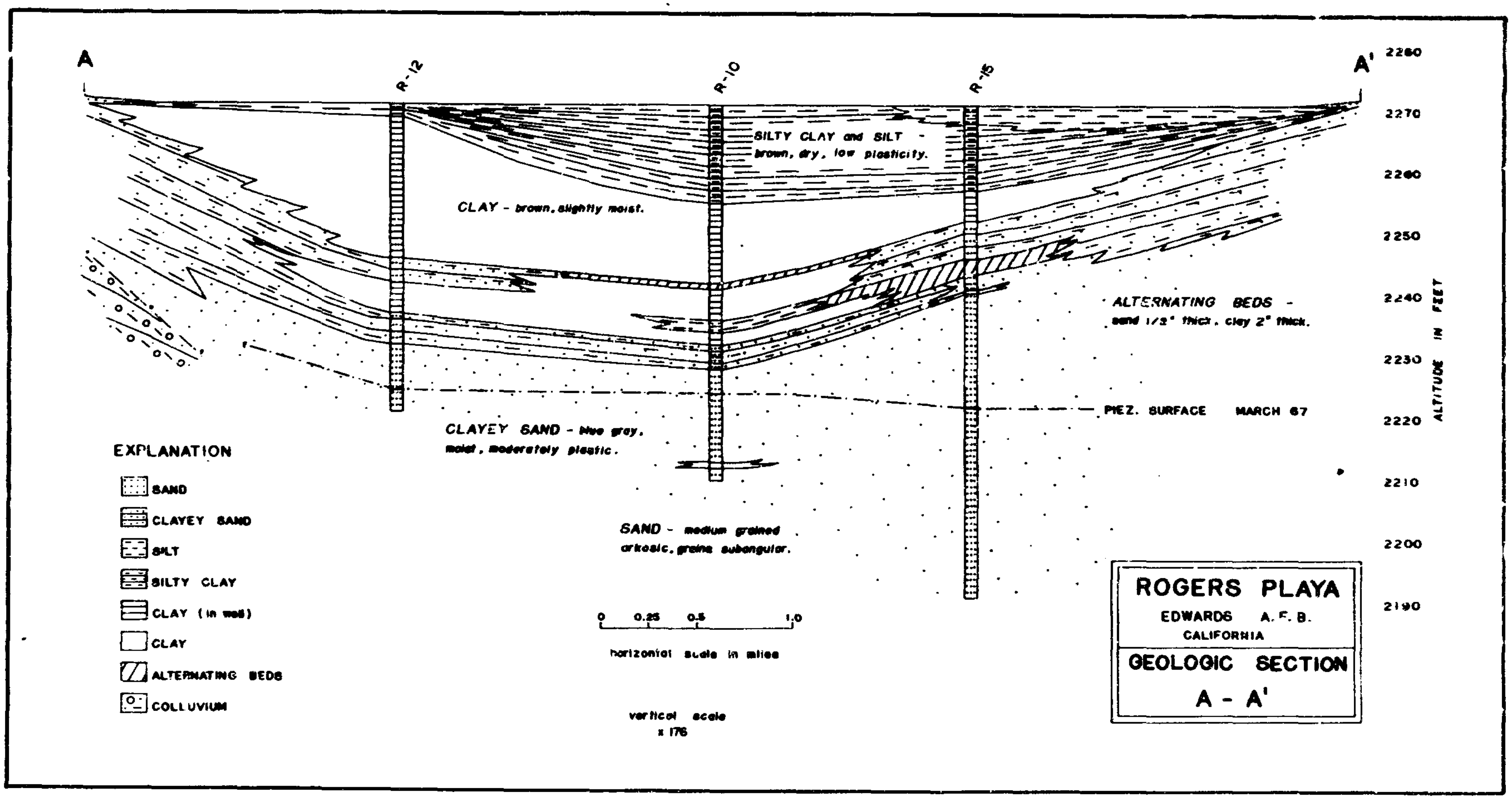


Figure 17. Geologic section A-A', Rogers Playa. See Fig. 16 for location of section.

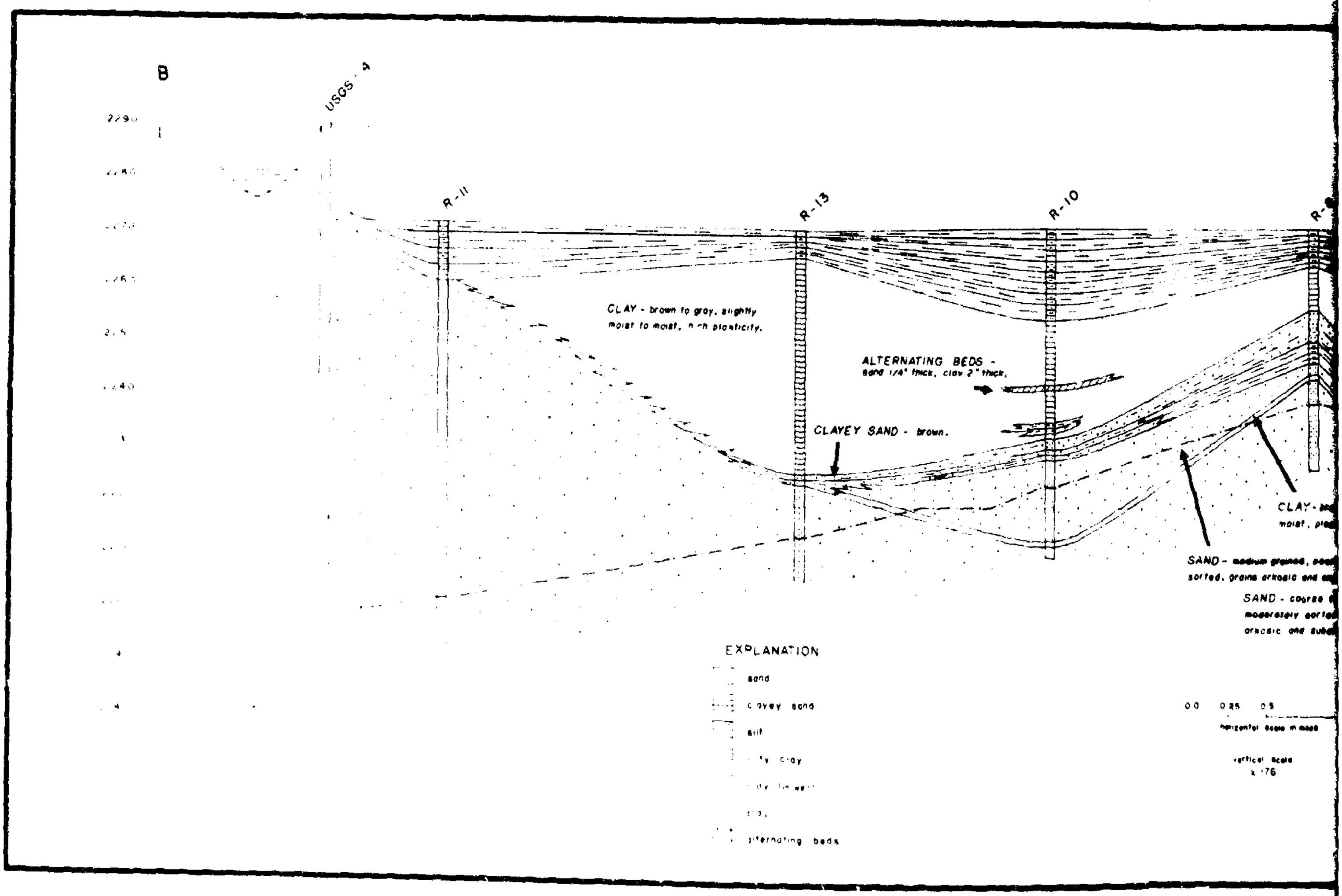
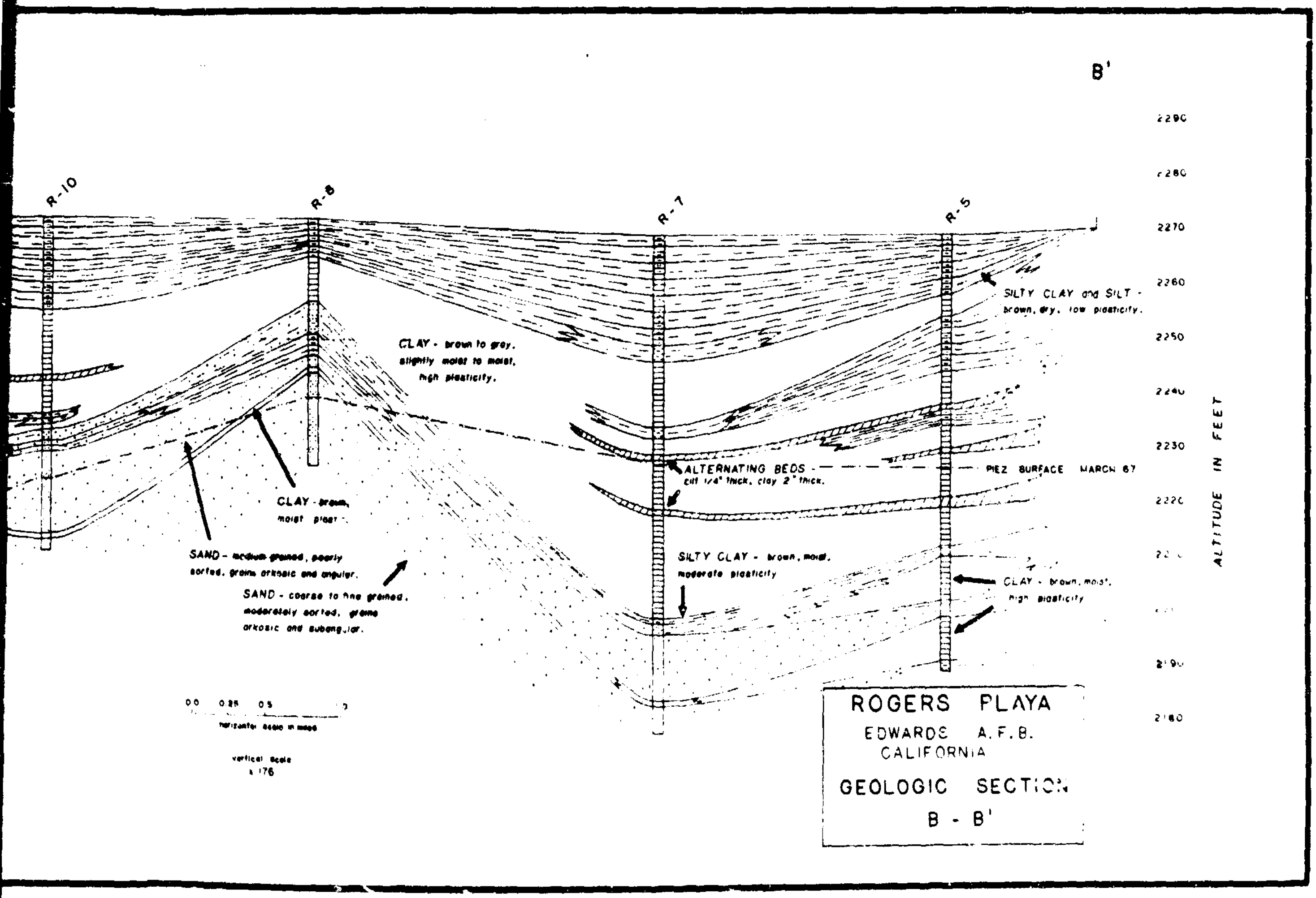


Figure ... Geologic section B-B', Rogers Playa

A



B'
2290
2280
2270
2260
2250
2240
2230
2220
2190
2180
ALTITUDE IN FEET
R-10
R-8
R-7
R-5
SILTY CLAY and SILT - brown, dry, low plasticity.
CLAY - brown to grey, slightly moist to moist, high plasticity.
ALTERNATING BEDS - silt 1/4" thick, clay 2" thick.
PIEZ SURFACE MARCH 67
CLAY - brown, moist
SAND - medium grained, poorly sorted, grains arkosic and angular.
SAND - coarse to fine grained, moderately sorted, grains arkosic and subangular.
SILTY CLAY - brown, moist, moderate plasticity
CLAY - brown, moist, high plasticity
horizontal scale in miles
vertical scale
ROGERS PLAYA
EDWARDS A.F.B.
CALIFORNIA
GEOLOGIC SECTION
B - B'

β

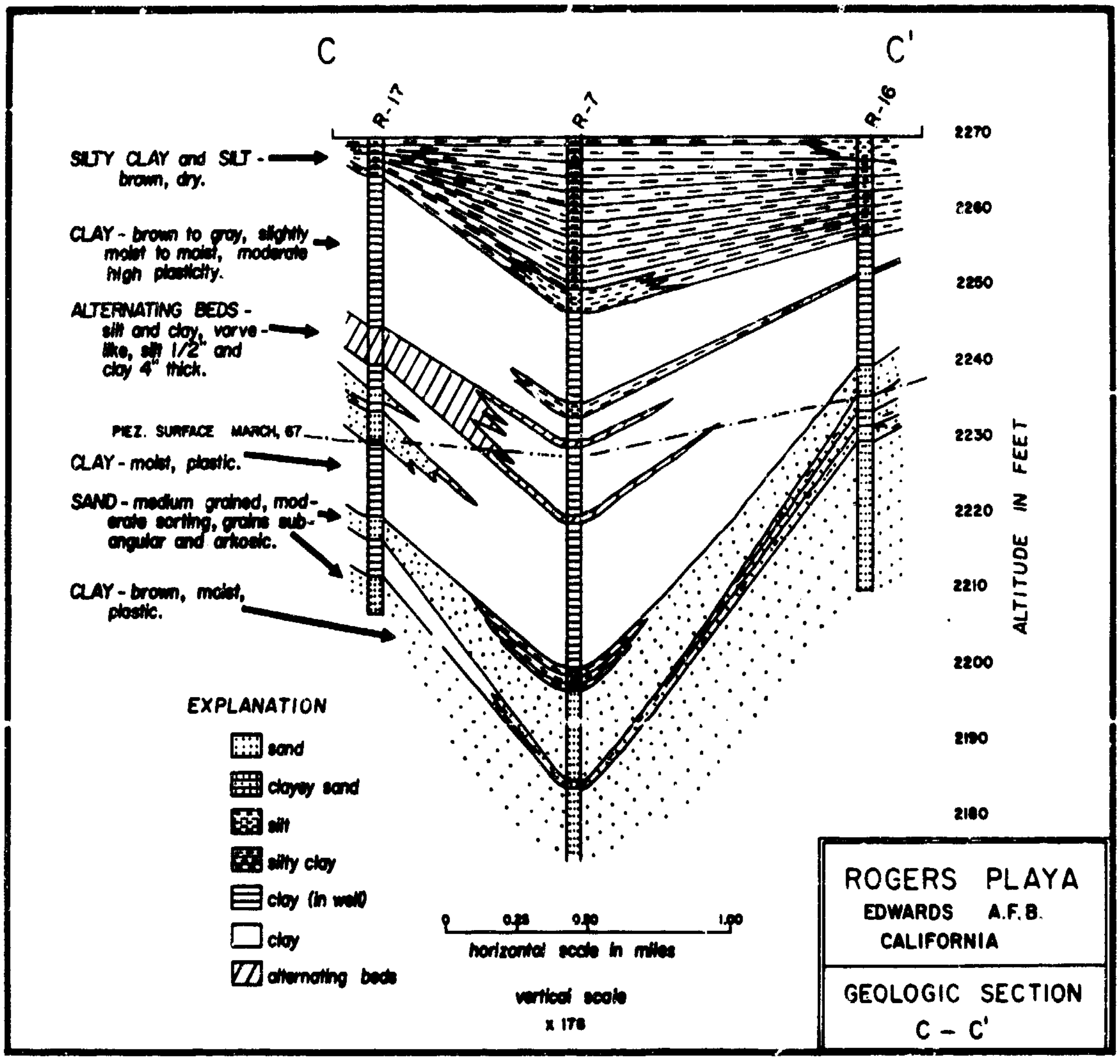


Figure 19. Geologic section C-C', Rogers Playa. See Fig. 16 for line of section.

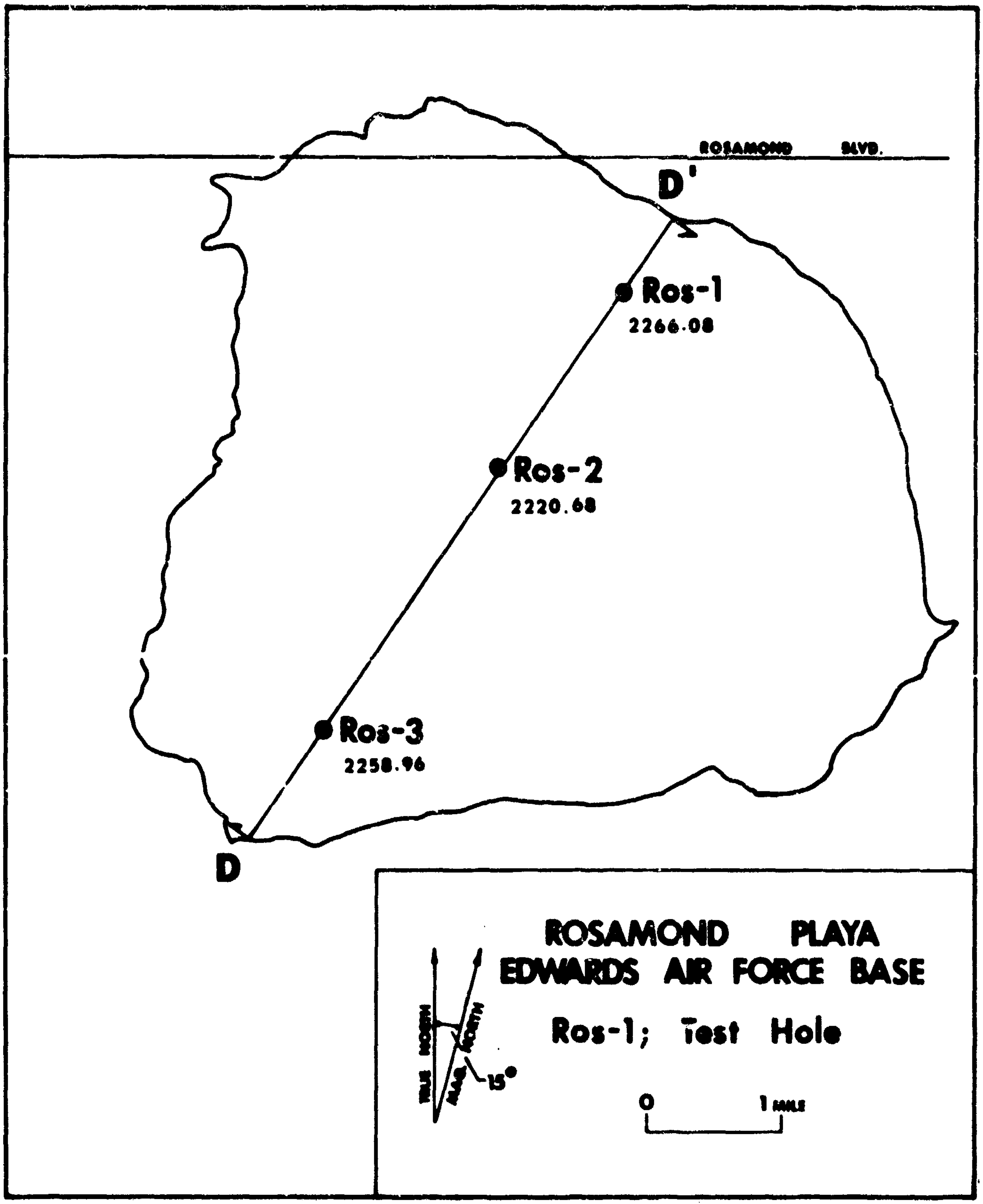


Figure 20. Map of Rosamond Playa showing line of cross section D-D' and elevations of potentiometric surfaces in test holes, August, 1966.

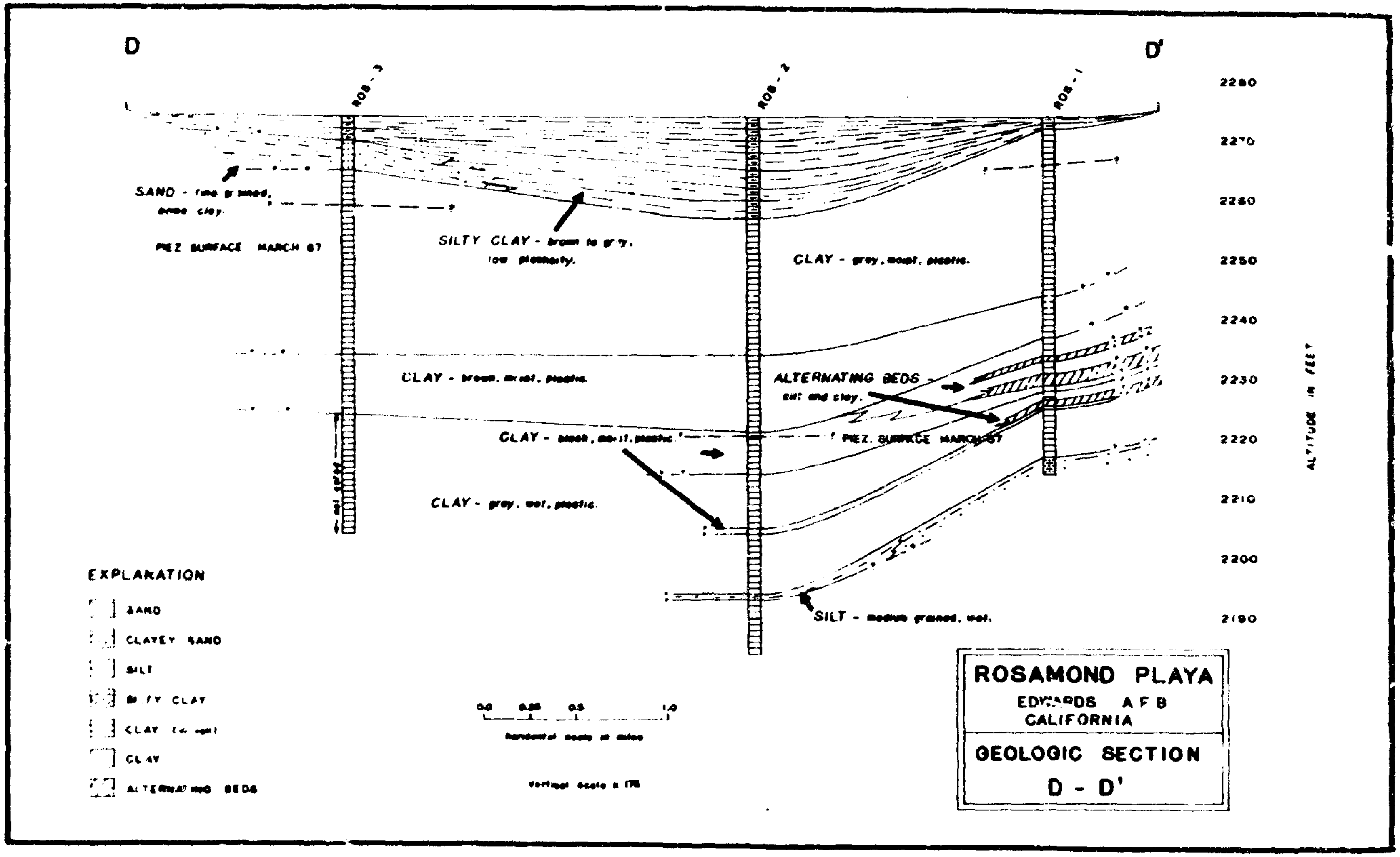


Figure 21. Geologic section D-D', Rosamond Playa. See Figure 20 for line of section.

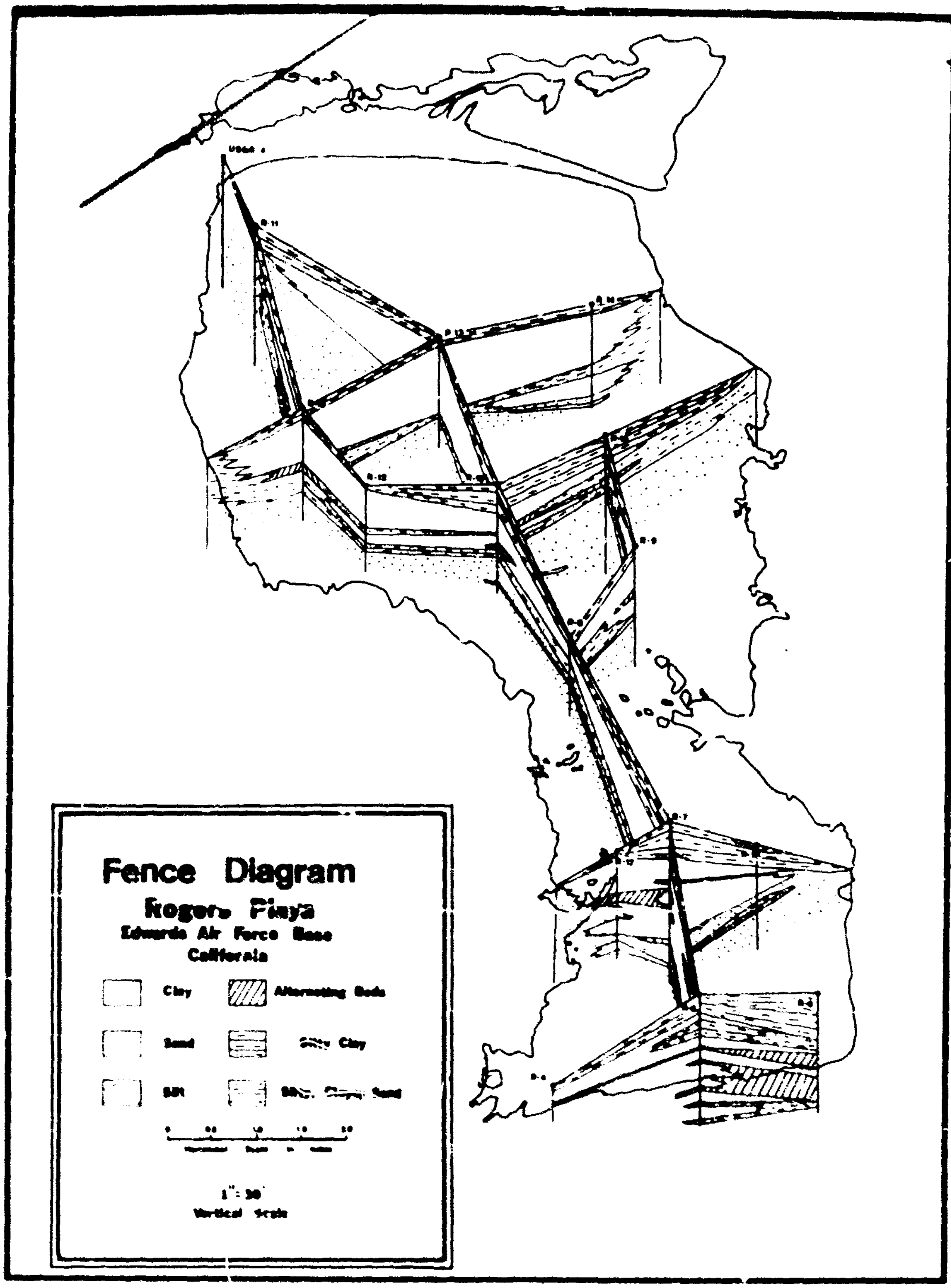


Figure 22. Fence diagram showing interfingering of Lake Thompson deposits underlying Rogers Playa.

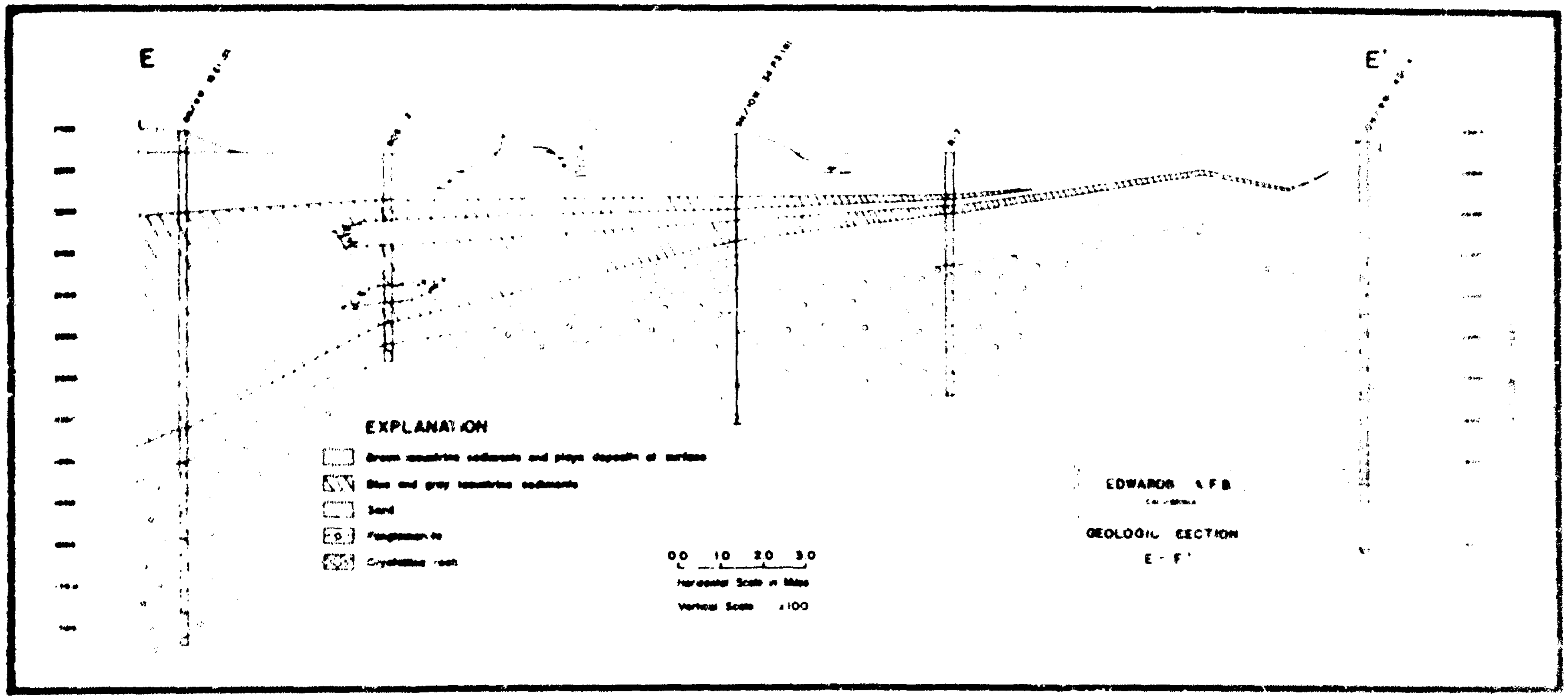


Figure 23. Geologic section E-E' showing thickening of blue and gray silts and clays to south and west of Rogers Playa. See Figure 24 for line of section.

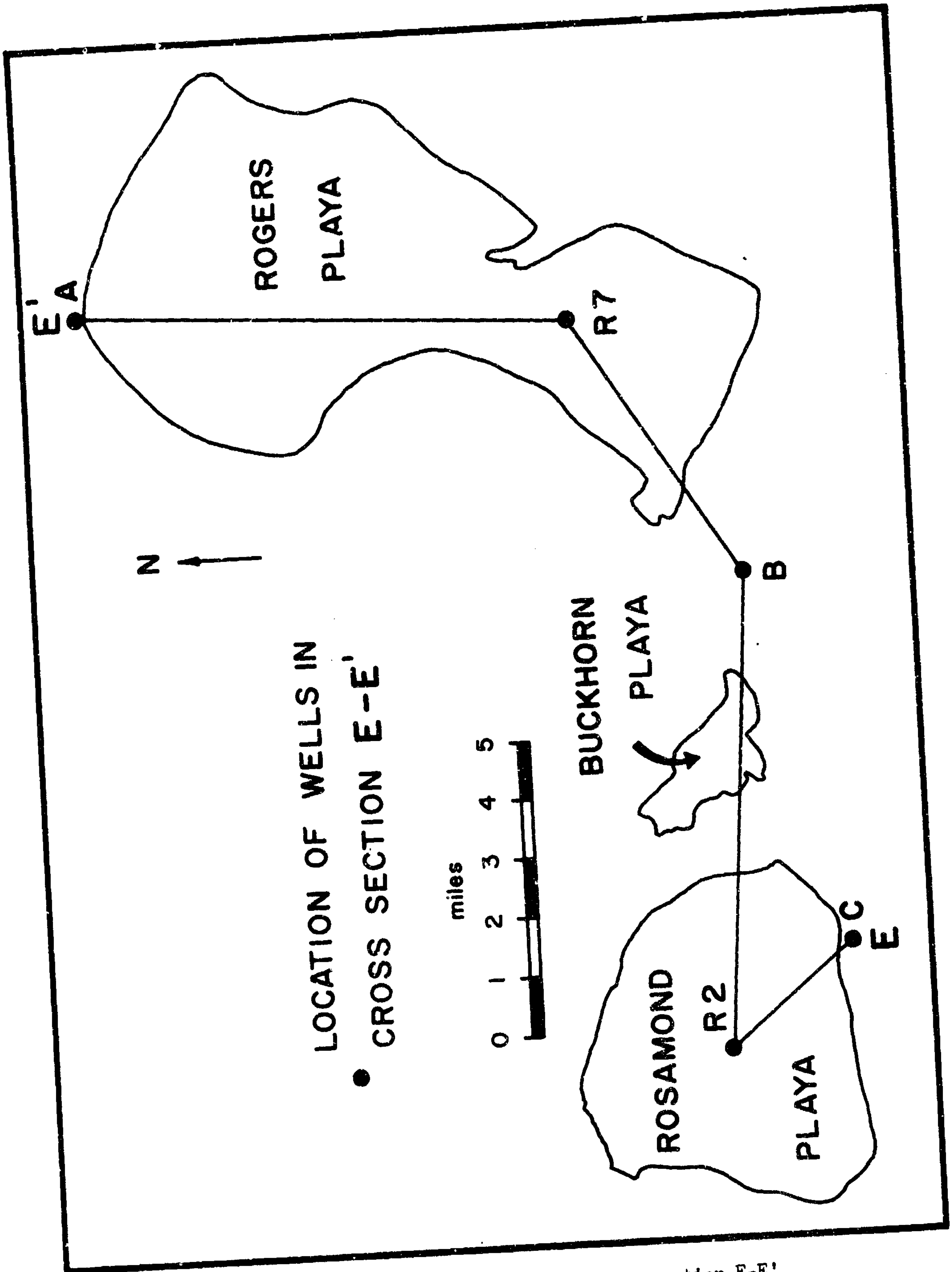


Figure 24. Location map for geologic section E-E'

thickest part of the silty clay unit of Rogers Playa generally corresponds with areas of thickest accumulation of fine-grained sediments. Near the center of Rosamond Playa, the silty clay unit thickens to about 20 feet. The silty clay unit of both playas generally has moderate to poor plasticity and is highly calcareous. Fragments of calcareous material are common in some parts of the unit, and desiccation cracks have been found in the more calcareous beds. The silty clay unit has numerous calcite-silt laminations. Silt in the unit is predominantly quartz with some feldspar and biotite flakes.

A clay unit underlies the upper silty clay in all parts of Rogers and Rosamond Playas (Figs. 17-21). The clay is highly plastic, moderately moist, and extremely fine-grained as shown by laboratory size analyses. Samples from both Rogers and Rosamond Playas show a high content of clay-size material that generally comprises most of the total sample. The unit has characteristic color variations. The upper part of the unit is reddish brown in color and grades into an underlying grayish blue. At the boundary of the color change, streaks of gray and brown clay appear to cross bedding planes and commonly occur as swirls and convolute forms.

A thin bed of moist clay occurs within the sand unit that underlies the fine-grained playa deposits. This plastic clay is a few feet thick throughout most of Rogers Playa and occurs about 2 to 15 feet from the top of the sand. The thin bed of clay grades laterally into silt and sand along margins of the playa. It forms an excellent stratigraphic marker.

Varve-like alternating beds of silt and sand with clay occur in Rogers Playa and Rosamond Playa (Figs. 18 and 21). The silt and sand beds are about 1/4 inch thick and consist mostly of medium to coarse silt with abun-

dant mica flakes. The clay beds range in thickness from 2 to 6 inches and consist of moist fine clay and silty clay. The alternating beds grade laterally into silty and clayey sand in the northern part of Rogers Playa (Fig. 17). Two other types of rhythmical bedding occur in sediments of Rosamond Playa. (1) In all three test holes on Rosamond Playa, there were laminations of alternating clay and calcite forming couplets that may be varves. (2) Another type of rhythmical couplet is formed by a difference in grain size from coarse to fine silt size.

The core from Rosamond 1 at 41 to 43 feet and at 49 to 50 feet has dark gray to black layers of a high organic content which may have originated during a time of intensive biologic activity in the lake.

The sediments of Rogers Playa differ from those of Rosamond Playa. Fine-grained sediments of Rosamond Playa contain more clay and were deposited under deeper water conditions than the fine-grained sediments of Rogers Playa. It is noteworthy that pollen from test holes at Rogers Playa was abraded, badly oxidized, and not identifiable, whereas pollen from Rosamond Test Hole 1 was unaltered and could be identified.

In both Rogers and Rosamond Playas lenses and beds of coarse silt and fine sand are interbedded in the fine-grained blanket. These coarser-grained units interfingor with the fine-grained deposits along the playa margins and have influenced the development of giant desiccation polygons.

HYDROLOGY AND SOIL MOISTURE

Dutcher and Worts (1963, p. 117, 118) show that two major aquifers underlie Rogers and Rosamond Playas--the "Principal Water Body" (Shallow Aquifer of this report) and the "Deeper Aquifer". Water in the Shallow Aquifer is largely in the Younger Alluvium which includes playa deposits and associated sand and silt lenses of Rogers and Rosamond Playas. Most water in the Deeper Aquifer is in the Older Alluvium. Prior to 1940, throughout the Lancaster Basin, the potentiometric head of water was higher in the Deeper Aquifer than in the Shallow Aquifer and generally higher than the playa surfaces. A large amount of discharge occurred through the playa surfaces, and a spring was reported in Rogers Lake (Dutcher and Worts, 1963, p. 141). After 1940, the head of water in the Deeper Aquifer was depressed below that of the Shallow Aquifer because of increased withdrawals from the Deeper Aquifer. The reversal of heads caused draining of water from the playa sand lenses into the Deeper Aquifer. Lowering potentiometric heads below the sandy zones may have resulted in reduction of water content in the fine-grained clays and silts. This dewatering and desiccation of playa sediments may be a primary cause of the formation of giant polygons (Neal and Motts, 1967). The sequential development of giant polygons is shown in Figure 25.

Water was encountered under hydrostatic pressure in each of the test holes. Also, the level to which the potentiometric head rose in each hole was below the surface of the playa. At Rogers Playa the maximum rise of water, 40 feet, occurred in Test Hole 6; and the minimum rise of water, 2 feet, occurred in Test Hole 11. At Rosamond Playa water rose 50 feet in Test Hole 1.

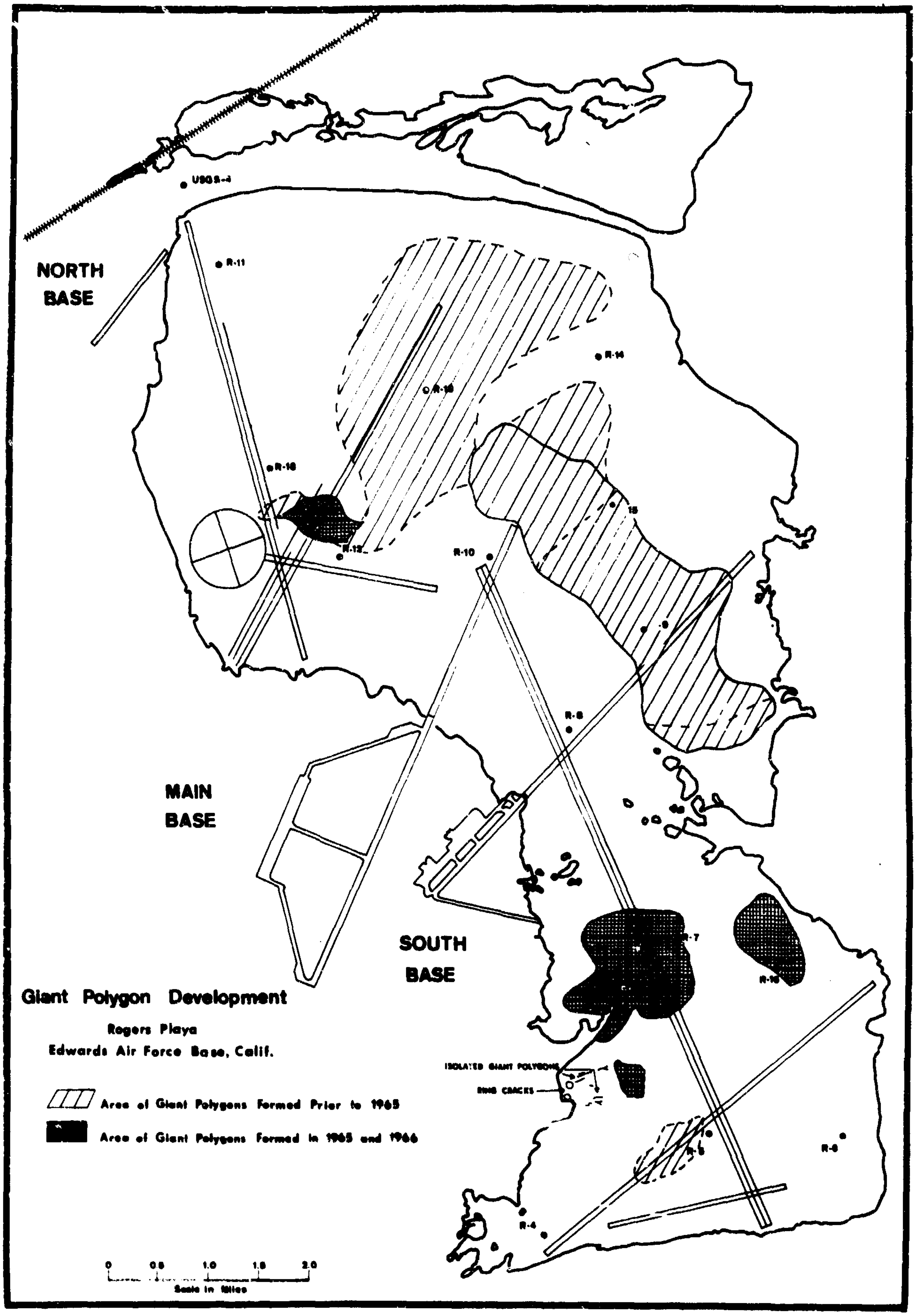


Figure 25. Sequential development of giant desiccation polygons, Rogers Playa.

Both Rogers and Rosamond Playas have depressed potentiometric surfaces along sedimentary axes of the thickest clay and silts. At Rosamond Playa in Test Holes 1 and 3 the potentiometric surface is 40 to 50 feet above the deeper potentiometric surface penetrated by Test Hole 2. The higher potentiometric surfaces along the margins of Rosamond Playa are due to saturated sand and silt lenses that interfinger with playa deposits. At Rogers Playa the depressed potentiometric surface occurs along an axis through Test Holes 7 and 5 (Fig. 16). As indicated in Figure 19, the potentiometric surface generally coincides with the thickest section of fine-grained deposits. A sharp rise of soil moisture in Test Hole 17 on Rogers Playa indicated a water-bearing zone from 22 to 35 feet; however, dry clays occur at 40 feet, indicating deep seated desiccation.

Soil moisture contents were determined from gravimetric tests of samples collected and weighed in the field and analyzed in the laboratory (Motts and Carpenter, 1968, Appendix B). From a study of logs and corresponding moisture contents a few generalizations were made. First, soil moisture content is closely related to the texture of the sediments; where the sediments become more silty and sandy, the moisture content decreases. This explains abrupt fluctuation of moisture curves on most logs down the hole. Second, moisture of fine-grained sediments increases downward in many of the test holes, for example in Rosamond 2. Third, in some test holes, for example Rogers 15, 17, and 18, clays above sand zones showed considerable loss of moisture, indicating desiccation of the playa deposits in the central and northern part of the Playa. It should be noted that throughout this part of Rogers Playa the potentiometric surface has lowered within the extensive sand and gravel body, thus allowing capillarity and

gravity drainage from overlying fine-grained silts and clays (Figs. 17 and 18). Capillary movement would occur if the sand units were in physical contact with the clays and were filled with water.

Soil moisture limits for test-hole samples from Rogers Playa were plotted for the years 1965 and 1966 (Motts and Carpenter, 1968, Fig. 10). Both curves show a gradual increase of soil moisture to depths of 15 to 25 feet. At this depth range, the 1966 curve shows a larger spread towards the drier side, which indicates that desiccation may have occurred from 1965 to 1966. It is noteworthy that severe floodings of Rogers during 1965 and 1966 had little effect on the soil moisture curves during 1966. Water stood on the playa surface from mid-November, 1965, through April, 1966. The 1966 curves show no appreciable increase of shallow soil-moisture content, revealing low permeability of the clays. Surface-water infiltration into the playa clays may be impeded by upward movement of capillary water.

CONCLUSIONS

The surface morphology of Rogers and Rosamond Playas changed significantly from 1964 to 1968 principally because of flooding in winter months. Each flood deposited a thin sedimentation unit that in many places graded from sand and silt near the base to clay near the top. Upon drying, each unit fractured into small polygons which curled upward to form "mud curls." Wind erosion further broke up the curls and made them susceptible to deflation. Except for the mud curls, the following playa types belonged to Stone's general category of smooth hard surface: (1) an extremely smooth and hard compact surface; (2) a more irregular, puffy surface than type 1, characterized by relatively high porosity with many eroded desiccation polygons; (3) a transitional surface containing areas of both the smooth hard and the puffy types; and (4) a smooth surface covered with a white crust of salt and carbonate. Numerous rosette impressions in 1968 were caused by ice crystals forming and pressing into the soft playa mud. The rosettes indicate that water in the playa lakes had frozen. Air Force personnel reported that the playa lakes freeze and thaw many times during the winter. This alternate freezing and thawing probably helped shatter the playa surface expecially where ice formed within large polygonal cracks. After evaporation of water from the playas in the winter of 1968, the surfaces were especially prone to wind erosion.

At Rogers Playa and Rosamond Playa fine-grained silt and clay form a relatively thin blanket which rests on a much thicker deposit of sand and gravel. The silt and clay blanket thickens in a southward direction from about 45 feet in the north part of Rogers Playa to more than 200 feet in Rosamond Playa. Within the blanket blue and gray clays also thicken from

Rogers Playa to the south. The silt and clay blanket contains four predominant sediment types: (1) an upper silty clay, (2) a lower highly plastic clay, (3) varve-like alternations of silt or sand and clay, (4) lenses of silt and sand interbedded in the fine-grained deposits.

Water under hydrostatic pressure was encountered in the test holes on Rogers and Rosamond Playas, and at both playas a depressed potentiometric surface extended along the sedimentary axis of thickest clays and silts. Soil moisture contents of samples from test holes showed a general downward increase of moisture in fine-grained sediments of the same size and showed a decrease in moisture content where the sediments became more silty and sandy. At some test holes (Rogers 15, 17, and 18) clays and silts above the sand zones showed considerable loss of moisture which indicated desiccation of the fine-grained deposits. Throughout parts of Rogers Playa the potentiometric surface has lowered within the extensive sand and gravel body, thus allowing capillarity and gravity drainage from the overlying fine-grained silts and clays. Capillary movement occurs if the sand units are in physical contact with the clays and are filled with water. Because of the relationship of the potentiometric surface to the clay and silt blanket and because of its lesser thickness, giant desiccation polygons have formed over a more extensive area and over a longer period of time on Rogers Playa than on Rosamond Playa. The position of the potentiometric surface, within the thick clays, of Rosamond Playa has retarded extensive desiccation. Giant desiccation polygons have formed only along the margins of Rosamond Playa where sand and gravel lenses interfinger with thick silt and clay deposits and where the potentiometric surface may have lowered within these lenses, thus facilitating subsurface desiccation.

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CHAPTER 3, PART 1: GEOLOGY AND HYDROLOGY OF COYOTE PLAYA

Excerpts from Thesis of David J. Hagar*

ABSTRACT

Coyote Lake occupies the central portion of a basin bounded on the north, west, and east sides by mountains of moderate relief and on the south side by a broad plain extending to the Mojave River, which crosses this plain nine miles south of the playa.

The areas surrounding the playa show evidence of a former, perennial lake, interpreted to be Lake Manix No. 2, of which the Coyote basin was an embayment. The lake is tentatively correlated with Tioga glaciation in the late Pleistocene. Benches were eroded in older fans by wave action, and a large bay bar was built out from the eastern edge of the lake. South of the playa, stream-channel deposits form a distributary pattern, presently expressed on the ground by a system of more or less coherent ridges originating in the vicinity of the Mojave River and extending into the Coyote basin. The broad area covered by the ancient stream deposits is designated a desert fluvial plain, and it is considered to be a relic feature related to the waning stages of Lake Manix. The formation of the desert fluvial plain isolated the Coyote embayment, and Lake Manix was confined to an area only slightly larger than the presently exposed playa surface.

The lake sediments underlying the playa are very fine-grained and compact, and have clay contents as high as 87%. Changes of the playa surfaces are interpreted as resulting from moisture changes of the clays near the surface due to floodings on the playa. Most of the playa has a smooth, hard surface, but in some areas soft, dry, puffy surfaces occur. The extent and nature of these two surface types change with time. Areas characterized by puffy ground occuring in patches were observed where clays appeared to be undergoing change from puffy to hard surface. Although puffy surfaces commonly are associated with ground-water discharge on other playas, water from depth beneath Coyote Lake is supplying little moisture to the clays. The playa surface exhibits giant desiccation fissures which intersect and form polygons ranging from 100 to 300 feet across. The majority are relict fissures, filled with sediment, and many of these may be very old, having developed as a result of the release of tension produced by very slow drying of clays during the time following the last humid episode.

Relationships in marginal zones of the playa suggest that the playa is not aggrading permanently, although material is brought to the playa during periodic flooding. The presence of loose, coarse detritus on the clay surface suggests that the fine materials were deflated.

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*Part 1 consists of edited excerpts from the unpublished Ph.D. thesis on Coyote Playa by Hagar (1966) included with his permission and abstracted by the editor.

INTRODUCTION

Hagar conducted field work on Coyote Playa during the summers of 1963 and 1964 under the guidance of Professors Ward Motts and H. T. U. Smith of the University of Massachusetts. His study was one of the first funded by AF 19-628-2486. John Schroeder, Charles Groat, William Gordon and Duncan Hagar assisted David Hagar during various stages of the field work. Pierre St. Amand of the U. S. Navy Testing and Ordinance Station, China Lake, California, gave advice and assistance to the study. Capt. J. T. Neal and G. H. Cabaniss conducted a seismic reconnaissance survey at Coyote Lake and assisted in the interpretation of the relation of this survey to the geology of Coyote Playa.

Geomorphic and Geologic Setting

Coyote Playa is situated in the east-central portion of the Mojave Desert of California. It is located approximately 20 miles northeast of the city of Barstow in San Bernardino County, and lies 8 miles north of Interstate Highway U. S. 15 (Chap. 1, Fig. 4). Desert roads offer access for the average vehicle. Coyote Playa lies in a basin bounded on three sides by mountains of moderate elevation. These mountains include Alvord Mountain east of the playa, Noble Dome to the north, and the Paradise Range to the northwest, with Lane Mountain and the Calico Mountains forming the western and southwestern flanks (Chap. 1, Fig. 4). A broad plain lies southeast of the playa and opens into a larger valley of which Coyote valley forms a northern extension. The channel of the Mojave River crosses this larger valley about 9 miles south of the playa. The plain continues south of the Mojave River where Troy Playa lies near the southeastern end of the main basin. The maximum elevation of the southern plain above the level of the

playa is about 80 feet. It is broken only by a few isolated low hills. Coyote Playa lies at approximately 1,700 feet elevation and occupies the lowest portion of the broad valley crossed by the Mojave River. Both Troy Playa and the river bed of the Mojave River above Afton Canyon are at slightly higher elevations.

The Calico Mountains, Lane Mountain, the Paradise Mountains and the Alvord Mountains are underlain by a basement complex of igneous and metamorphic rocks (McCulloh, 1952; Byers, 1960). On the northeastern side of the Calico Mountains, McCulloh has described a 26,000-foot section of metamorphic rock which he considers to be derived from clastic sediments of Paleozoic age (1952, p. 7-56). The metamorphic rocks have been intruded by a wide variety of plutonic rocks, and although the age of these has not been established definitely, they are probably Mesozoic (McCulloh, 1952, p. 71-103). Rocks of Tertiary age lie uncomformably over the basement complex in many locations. With the exception of the Barstow formation, probably of upper Miocene age, only tentative correlations have been made between the formations in the Alvord Mountain and Lane Mountain quadrangles. The Barstow formation has been traced from its type locality in the Barstow syncline eastward into the Calico and Alvord Mountains, suggesting that this area was a large Tertiary basin at one time. The central part of the basin may have been near the Calico Mountains, and Byers (1960, p. 34) suggests that it may have contained a chain of playas separated by gravel fans. A granitic fanglomerate found extensively in the Alvord Mountain quadrangle is assigned a Pliocene age by Byers (1960, p. 38) who reports that in one location, the fanglomerate grades downward into the Barstow formation of Miocene age. This suggests that the Miocene basin may have persisted throughout the late Tertiary and early Quaternary. Byers states that the

present Coyote Playa basin began to take form during early to middle Pleistocene time.

The movements that produced the basin in which Coyote Playa is located, as well as the mountains surrounding it, are typical of those that prevailed throughout the Mojave block during early to middle Pleistocene time. Pre-Tertiary rocks in the Calico Mountains and in the Alvord Mountain area have been folded and several faults can be traced in the area. The fault most closely connected with the formation of the Coyote valley depression is the Coyote Lake fault which has been traced in the Lane Mountain quadrangle by McCulloh (1953) using gravity surveys, and by Byers (1960) in the Alvord Mountain quadrangle. Indications are that in the western section of this fault, located 3 miles north of Coyote Playa, movement was downward on the south side, thus producing the basin occupied by the playa. In the eastern section in the Alvord Mountain area Byers (1960, p. 50) suggests that the north side is down-dropped relative to the Alvord Mountain upwarp to the south.

Previous Investigations

Although many investigators studying dry lakes visited Coyote Playa, no study was focused on the playa or on Coyote basin. Several quadrangles in the area have been mapped, however. Byers (1960) mapped the Alvord Mountain quadrangle, and McCulloh (1952) mapped the northern half of the Lane Mountain quadrangle. Each of these quadrangles covers portions of the playa. A map of the Newberry quadrangle has been prepared by Dibblee and Bassett (1966), and a preliminary map of the Nebo and Yermo quadrangles by McCulloh (1965) is available. A description of Coyote valley was included in the reconnaissance of the Mojave Desert conducted by Thompson (1929). A hydrologic reconnaissance of the Camp Irwin area north and east of the playa, conducted by Kunkel and Riley (1959), includes the Coyote valley, and data on wells and springs in the lower Mojave valley were compiled by Dyer and others (1963).

Among the studies of playas, there are several which mention Coyote Playa. Stone (1965, p. 65), describing classifications of playas on the basis of surface types and ground-water conditions, designated Coyote Playa as the type for compound playas, one of five types in Stone's classification system. Neal (1965a, p. 9) cites Coyote Playa as an example of a playa exhibiting what he terms a "soft, dry, porous, puffy surface" in his field classification of playas. In an article on giant desiccation fissures, Neal and others (1968, p. 72-73) classifies the polygonal pattern of fissuring on Coyote Playa. Results of test drilling on Coyote Playa are reported by Motts and Carpenter (1968).

Studies in the lower Mojave valley related to the history of the area include one by Blackwelder and Ellsworth (1936) on the stratigraphy of Afton basin where beds of Pleistocene Lake Manix have been exposed by the down-

cutting of the Mojave River. Jefferson (1968) has described a faunal assemblage from the Manix beds and provides a basis for dating these sediments more accurately than was possible previously.

Climate

The mean annual temperature for the Coyote Playa area of the Mojave Desert is 65.9°, according to the U. S. Weather Bureau at the Daggett FAA Airport. A short period of low temperatures during the winter months accounts for this rather low figure in an area where summers are long and daytime temperatures frequently reach 100° and more.

Relative humidity averages between 30 and 40 percent. In the summer months during the daytime, humidity is often less than 10 percent (Troxell and Hofman, 1954, p. 13). Records for the year 1964 at the Daggett station show that the most frequent relative humidity, recorded during hourly observations of wind velocity, is 30 percent or lower. Coupled with the high temperatures, this low humidity results in a very high rate of evaporation.

Desert precipitation tends to be extremely variable, both in place and in time (Troxell and Hofman, 1954, p. 14); therefore, the annual precipitation in any specific basin is difficult to determine without at least one rain gauge in that basin. The rain gauges nearest Coyote Playa are located at Dunn Siding, 18 miles east of the playa, and at the Daggett FAA Airport, 14 miles west-southwest. Precipitation records for the Daggett FAA Airport indicate that annual precipitation ranges from slightly less than 1 inch to slightly more than 9 inches. Records for Dunn Siding, available only since 1961, show that precipitation amounts are similar to those at Daggett but are generally somewhat less. Information on rainfall and flooding on the playa itself is limited to reports from local residents and researchers who

make only sporadic visits. Residents report that on occasions during winter months, the playa has been flooded either partially or entirely.

Hourly observations at the U. S. Weather Station at the Daggett FAA Airport indicate that the most frequent winds are between 4 and 12 miles per hour. Next in frequency are winds of 13 to 24 miles per hour (U. S. Weather Bureau, 1964). During the summers when the author was in the field, there were several occasions when sand and dust storms were observed. On such occasions, it is common to see clouds of dust rising as high as 300 feet in the air above a playa.

GEOMORPHOLOGY OF COYOTE PLAYA AND ADJACENT AREAS

Types of Playa Surface

Coyote Playa has two basic types of surface: a hard, compact surface and a soft, dry, puffy surface. Intermediate types are transitional between these two. Study of the playa over a period of years indicates that the extent and character of the types of surface are subject to considerable change (Fig. 1).

Hard Compact Surface

Continuously hard compact areas are located in the central and northern sections of the playa, although portions of the northern section develop puffy conditions on some occasions. The hard surface is typical of that found on many playas of the dry type. Generally, areas of hard compact surface show little or no relief, and the clay has a very smooth surface covered with a system of very fine, irregular cracks which form polygons measuring approximately 3 to 4 inches across. In 1963 and 1964 the clay at the surface had a very pale buff color and extremely fine texture, and the clays immediately beneath the hard surface were indurated and massive.

The percentage of clay in the sediments of the hard surface is very high. An analysis to determine the sand:silt:clay ratios (see section on Analyses of Sediments from Coyote Playa) showed that the clay content of this type of surface is as great as 81.49 percent. Other figures representing the clay content of the hard surface were 80.16 and 80.13 percent. These figures are generally high compared with figures reported by Kerr and Langer (1965, p. 37) for selected samples from Rogers Playa, California, which is a typical hard-surfaced playa. Four samples from Rogers Playa ranged from 49.9 percent to 87.0 percent in clay content. It should be

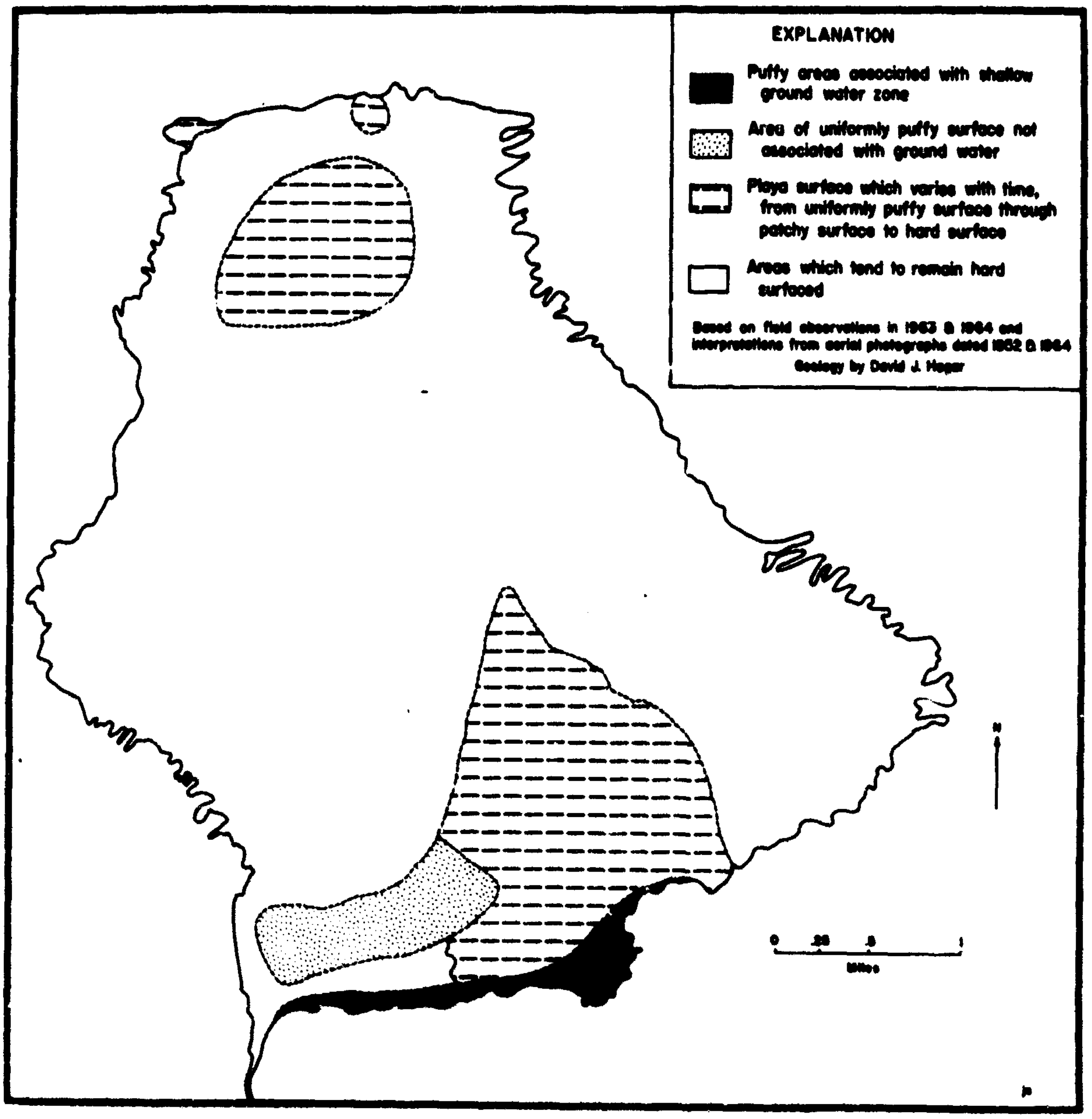

Figure 1. Map oi surface conditions on Coyote Playa, California (adapted from Hagar 1966, Pl. 2).

noted, however, that Kerr and Langer's percentages represent a slightly coarser range of sediment, since their clay:silt fraction was divided at 5 microns, whereas Hagar's was divided at 3.9 microns. The hard, dry condition which prevails on large areas of Coyote Playa is attributed by this author to a lack of significant discharge of ground water from depth beneath the playa. The playa is underlain by poorly permeable clays which prevent or significantly retard movement or discharge of ground water through this portion of the basin.

Changes in the hard surface, such as the development of puffy or transitional conditions, are best explained by environmental changes at the surface. The most significant variable factor in the environment affecting behavior of playa clays is moisture. Probable sources for this moisture are discussed further in the following sections of this report.

Soft, Porous, Puffy Surface

Areas of "self-rising" or puffy surface on Coyote Playa are characterized by a thin, uneven, easily-broken crust underlain by a layer of fine, dry, loose material. Beneath the loose material, the sediments are firm and compact. The color of the crust and the loose material beneath is light brown, noticeably darker than the color of the hard surface. In many places the crust is broken by thin, irregular cracks. Areas of puffy surface are caused essentially by the addition of moisture to clays. On many playas, the source of this moisture is ground water moving upward by capillary rise although, as described in this report, other sources of moisture are possible.

At least three basic variations of puffy surface can be distinguished on Coyote Playa. These are: (1) uniform areas of puffy surface, associated with ground-water discharge; (2) uniform areas of puffy surface not asso-

ciated with ground-water discharge; and (3) patchy areas of puffy surface which are undergoing change and may occur alternately in a puffy or hard condition. The first variation, associated with ground-water discharge, occurs chiefly along the western section of the southern marginal zone and is most nearly like puffy surfaces described on other playas (Thompson, 1929; Stone, 1956). Uniformly puffy surfaces not associated with ground-water discharge occur on the playa itself. One such area which extends eastward from Coyote Wash for about one mile appears to be stable and remains in a puffy condition. Other areas of puffy surface are unstable and are subject to change in distribution. At some times, these areas exhibit puffy ground occurring in patches and are interpreted as representing transitional conditions between uniformly puffy and hard surfaces. Transitional, or variable, areas were observed in both the northern and southern sections of the playa.

Along the western sector of the southern marginal zone of Coyote Playa, a puffy surface occurs at the top of the playa slope, which rises as much as 12 feet above the playa floor in this section. Puffy ground extends down the slope and onto the playa surface for distances ranging between 300 and 1,000 feet. In 1963 and 1964, the depth of the loose material in this zone ranged between 2 inches at the top of the slope to 12 inches along some sections of the slope. Depths of 4 to 8 inches were most common.

Seepage from a perched zone of ground water moistens the sediments on the slope. A trench dug in one of the steeper portions of the slope in the western sector of the southern marginal zone showed that several layers of sand and silty clay overlie a massive layer of poorly permeable clay which is continuous with the clay of the playa surface. A layer of saturated

sand immediately above the poorly permeable clay was identified as the layer from which water was seeping. Since the layers of sand and clay crop out along this embankment, ground water from the sandy layer discharges along the slope. The water has a relatively high saline content (1,400-1,500 ppm), and as it evaporates, salts are left in the sediments or on the surface. Salt encrustations near the top of the embankment are visible on aerial photographs.

The clays beneath the puffy material near the base of the playa slope are hard and dry. A hole augered by hand in 1963 at the base of the slope, 300 feet from the trench, penetrated 4 to 5 inches of loose material, and beneath this, dry clay was encountered to a depth of 90 inches. The clay becomes increasingly dry with depth, and the last few inches of clay were brought up in a powdered condition, having been ground up by the auger. At this depth, augering was very difficult, and the bucket tips became bent. A fresh sample taken at 4 feet was a-brittle, dry clay of light olive gray color.

The puffy surface immediately associated with the zone of seepage clearly is receiving its moisture from ground water. The puffy sediments at the top of the slope above the zone of seepage probably are moistened by capillary rise.

Uniformly puffy surfaces may be either stable and relatively constant or unstable with a tendency to become hard. Field observations of the playa, and examination of aerial photographs indicate that although uniformly puffy areas occur extensively on Coyote Playa at some times, only one area (exclusive of marginal zones) remains constantly in a puffy condition. This area extends in a band about 1,500 feet wide for a distance of about one mile

eastward from the vicinity of Coyote Wash which enters the playa at the southwest corner. Farther eastward, the puffy surface was uniform when observed in 1963, but in 1964 it was in a transitional stage and was becoming hard. Another uniform, but unstable, zone of puffy surface extends outward from a smaller wash in the northern marginal zone and appears clearly on aerial photographs taken in 1964, but it is not visible on the 1952 photographs.

Uniformly puffy areas are characterized by broad, uneven surfaces broken only by very small, local washes draining into low places. In general, the puffy surface in these areas is poorly developed and subject to change not only in extent but also in the depth of loose material. Whereas Stone (1956, p. 78) reported that depths of loose, dry material on playas range from 1 to 4 feet, the loose material on Coyote Playa seldom exceeded 8 inches in depth during the summers in which field observations were made. Furthermore, this depth is not constant. In the summer of 1963, the soft loose material was about 4 to 8 inches deep in most places, and it was difficult, although not impossible, to drive a car with 2-wheel drive across this surface. In 1964, in many of the same areas, driving was much easier, and the depth of the puffy material varied from only 1 to 4 inches. Compared to the puffy surface in 1963, the puffy surface in 1964 is best described as semi-firm.

Stone (1956, p. 90) proposed that the areas of hard and puffy surface which he saw on Coyote Playa were caused by variations in the depth to ground water, and that water must be within 10 feet of the surface beneath puffy ground. His description of puffy surfaces, in general, assumes that sediments become more moist with increasing depth. In order to check the

relationships suggested by Stone, sub-surface conditions were investigated. In 1964 a hole was drilled by power auger in the zone of puffy surface extending from Coyote Wash, and a depth of only 8 feet was reached. Unfortunately, drilling had to be terminated because of the extreme hardness of the clay. The clay encountered throughout the drilling process was olive gray, and just before drilling was terminated, clay was coming up as dry, hard chips. It was evident that the water table was not within 10 feet of the surface. Surface water probably moves through the surface layer of loose, porous clays and essentially is perched above the more compacted clays that lie beneath.

The relationship of uniformly puffy areas to washes entering the playa suggests that the source of moisture for upper clays in these areas may be the concentrations of runoff that occur during intervals of flow in ephemeral streams. The area extending eastward from Coyote Wash appears to remain continuously puffy in the area nearest the wash, and an area of uniformly puffy surface occurs at times near the northern marginal zone. The latter has been shown to be less stable, but it clearly was associated with a wash discharging onto the playa at the northern border.

Two samples of uniformly puffy surface were analysed for sand:silt:clay content; clay fractions of these two samples were 71.5 percent and 66.9 percent, respectively. These figures are slightly lower than figures obtained from samples of the hard, compact surface.

The high clay content of the puffy surface on Coyote Playa is not typical of puffy surfaces on other playas, according to figures presented by Kerr and Langer (1965, p. 34), who indicate that puffy surfaces usually are associated with playas where the clay content is less than 50 percent.

Although some areas of puffy surface are relatively constant, others are variable both in extent and character (Fig. 1). At some times variable areas are uniformly puffy, as described above, but at other times the puffy surface occurs in patchy spots and is interpreted as a transitional surface. These variable areas may exist at times as relatively hard-surfaced areas. An extensive variable area occurs east of the zone of more stable puffy surface extending from Coyote Wash. Another area of variable surface is located in the northern section of the playa.

It is likely that these transitional conditions occur where ground water is not supplying a constant source of moisture and where moisture content is variable. One suggested explanation for the several stages of behavior of the clay is that it may undergo a cycle of swelling and compaction. It is possible that when the clay is in a dry, porous state, having "puffed" or "risen", additional wetting causes this soft, porous material to collapse and become compacted. Thus, a cycle of wetting and swelling, drying and subsequent wetting and collapse, may be responsible for the changing appearance of the surface clay.

Conclusions on Playa-Surface Types

Puffy ground affected by surface moisture evidently differs in several respects from that affected by ground water. In the zone along the southern border where seepage of ground water is associated with the development of the puffy surface, it is significant that there was no appreciable variation in extent or depth of loose material, and clays tended to remain puffy only where associated with a concentration of runoff. These changing conditions are explained most logically by the fact that surface runoff supplied a much less constant source of water than capillary rise or seepage from

ground water. The most variable areas do not receive concentrations of runoff, but probably receive moisture only from precipitation or general flooding of the playa.

The high clay content of the puffy surface on Coyote Lake indicates that, although a slightly lower clay fraction may favor development of this condition, it can occur where clay fractions are relatively high. This suggests that the mineralogical composition of the clay may be of greater significance than physical properties such as granular size. Kerr and Langer (1965, p. 68) indicate that they did not find clay assemblages to be diagnostic for any type of playa surface, although they report that montmorillonite and illite are commonly found in playa clays. According to Grim (1962, p. 247-251), these clay minerals may possess the capacity to swell under certain conditions. Grim indicates that if only part of the non-cellular water has been driven off, rewetting can cause clays to swell; but if all non-cellular water and some cellular water is driven off, then swelling will take place during rewetting only with great difficulty. Therefore, it is possible that the self-rising property of the clays on Coyote Lake is basically an inherent property of the type or types of clay, acting in combination with varying moisture conditions. More investigation of the clay-mineral assemblages is necessary before this can be stated conclusively. It is suggested that the clays on Coyote Lake offer opportunity for study of mineral composition and physical properties of clays, and their behavior under a variety of conditions of moisture supply.

Giant Desiccation Fissures and Drain Holes

Most of the surface of Coyote Playa is covered by giant desiccation fissures, or cracks, many of which are filled completely at present and are sites of plant growth. The fissures intersect approximately at right angles and form polygonal patterns which are best seen from the aerial view. The length of the fissures on Coyote Playa typically ranges from 100 to 300 feet. On aerial photographs, the appearance of fissures and polygonal patterns differs in character from one location to another on the playa. Fissures are commonly encountered during traverses across the playa and each of the developmental stages of giant desiccation fissures described by Neal, Langer, and Kerr (1968, p. 84) has been observed. Relic outlines, defined by Neal (1965b, p. 19) as older fissures which have been filled with sediment, comprise the majority of fissures on Coyote Playa, but on each occasion when the playa was visited, fresh or relatively fresh fissures were seen.

The patterns of polygonal systems on Coyote Playa fall into two classification categories, according to Neal and others (1968, p. 72-73). Relic fissures are generally regular and random-orthogonal in pattern, whereas fresh fissures are irregular, random-orthogonal. The majority of fissures covering the surface of the playa have a regular, random-orthogonal pattern.

Fresh fissures are essentially wedge-shaped in vertical cross-section. Typically, they are partially filled with loose, angular debris which has broken and fallen from the side of the fissure. The walls are rough, jagged and irregular in the opening of a very fresh fissure, and slumping occurs, particularly in large fissures. At the surface, fissure openings have maximum widths ranging from six inches to three feet. This width varies considerably along the length of an individual fissure, and it gradually

decreases laterally toward the ends until the fissure is only a fine, irregular fracture in the clay and measures only a fraction of an inch in width. The depth of the visible opening generally does not exceed 1 or 2 feet, although it is possible to probe through the debris to depths of four feet. Presumably the actual depth of the fissure is much greater. According to geophysical investigations by Cabaniss (1965, p. 8) on Rogers Playa, fissures may extend to depths of 20 to 30 feet. Fresh fissures on Coyote Playa commonly have a secondary set of fractures which parallel the open fissures on each side. These vary in dimension according to the size of the main fissure, but they commonly range from about 1/2 to 2 inches in width and 6 to 18 inches in depth, and are found approximately 6 to 10 inches from the edge of the main fissure opening.

Fissures which are relatively fresh, but which have been subjected to one or more seasons of flooding, remain as open cracks in the playa surface, but show evidence that water flowed into the fissure. Debris in the opening has been reworked and consolidated and is no longer angular or loose. Water-laid sediment has begun to fill the spaces, and mud cracks in the reworked materials offer unmistakable evidence that water has been present.

Conical or irregularly-shaped depressions occur at numerous locations on the playa in association with giant desiccation fissures, including relic outlines. These range in size from 8 inches to almost 4 feet in diameter at the playa surface. The sides develop pronounced mud cracks which are wider and deeper than those that occur in the surrounding playa surface, and the center of the depression may contain an opening down which water flows when flooding occurs, according to field observations by Kunkel and Riley (1959, p. 253-254). Commonly, one or more small drainage channels

indicate where water entered the depression. Well-developed examples are present in both the hard and puffy surfaces of the playa.

Depressions of this type have been reported on a number of playas. Kunkel and Riley (1959, p. 253) noted these features on Coyote Playa and termed them "drain holes." Dutcher and Worts (1963, p. 44) described similar features in the northeastern portion of Rogers Playa, and Motts (personal communication) observed that drain holes on Rogers Playa are associated with the junctions of fissures. Stone (1956, p. 112-118) described these features but attributed their development to escaping gasses from subsurface sediments. On Coyote Playa, drain holes form along fissures and at their junctions, suggesting that they develop as water flows downward through fissure openings.

Marginal Zones and their Geomorphic Relationships

Areas marginal to playas differ considerably from one playa to another and around any one playa. Distal ends of alluvial fans and eolian deposits may obscure the extent of playa clays, hence playas are not marked by clearly-defined boundaries. Recognizing this, Stone (1956) described a zone existing around many playas and termed it a "transition zone." Because relationships described by Stone (1956, p. 148) were not observed around Coyote Playa, transition zones are not designated here. Instead, "marginal zones" are described which include a periphery of the exposed playa surface and areas immediately surrounding the playa. The extent of the marginal zones around Coyote Playa and their designations as used in the text are shown on the sketch map (Fig. 2).

The northeastern marginal zone of Coyote Playa is formed by the distal portions of alluvial fans which are composed primarily of volcanic material. Two fans descend from Alvord Mountain and a third from the low pass north-

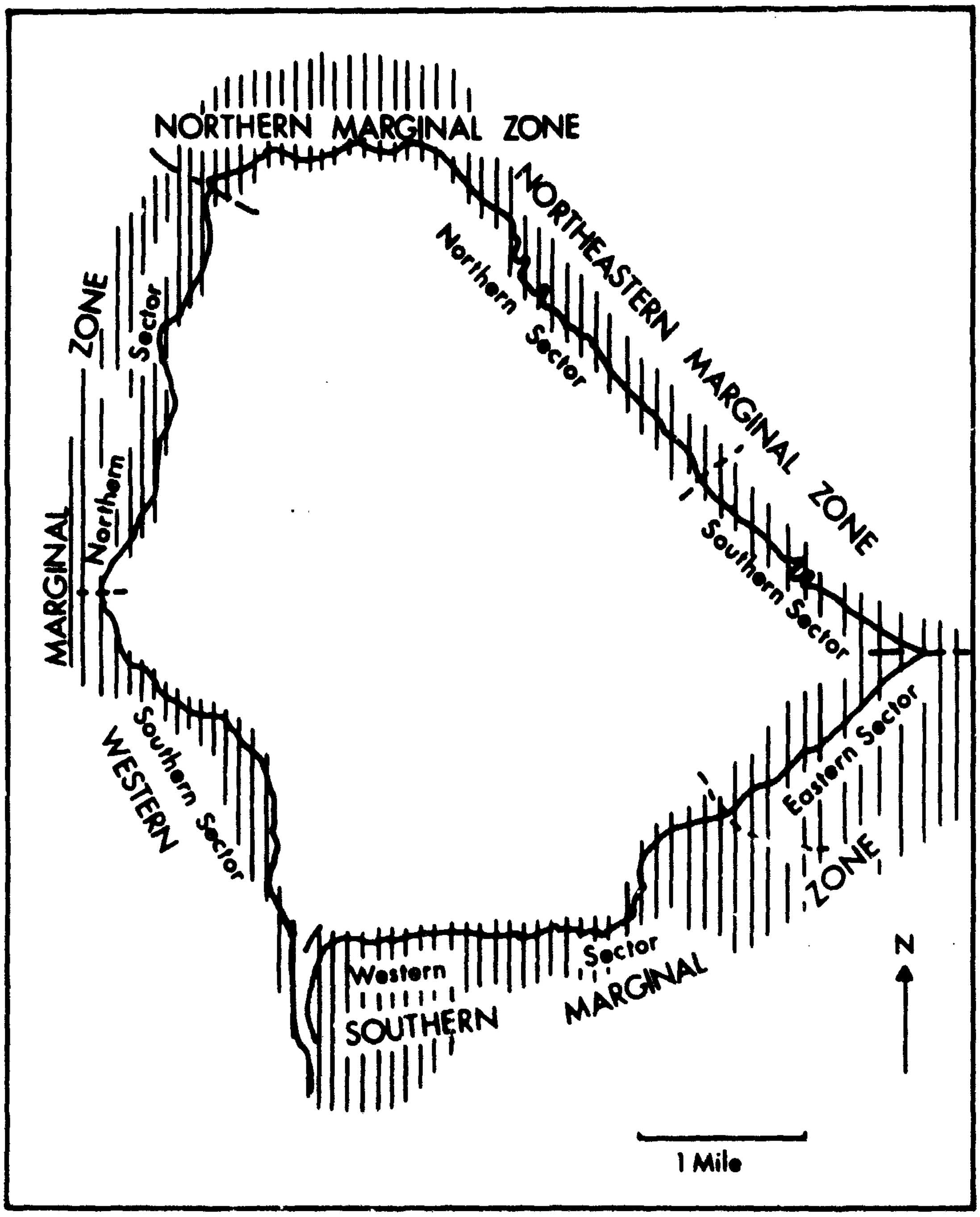

Figure 2. Sketch map of Coyote Playa showing the playa marginal zones. The approximate extent of the marginal zones is shown by the hachure lines. (Adapted from Hagar 1966, Fig. 4.)

east of the playa. Near the edge of the playa itself, along this margin, the clays slope gently upward toward the alluvial fans and continue under the alluvium.

The northern marginal zone is narrow and the playa edge is poorly defined here. A band of sand dunes, stabilized by vegetation, characterizes the eastern part of the marginal zone, and a blanket of hummocky sand covers the western part. On the playa itself, plant mounds occur independently of fissure outlines and the sediments have a tendency to develop a puffy surface.

Along the entire western marginal zone, alluvium forms a thin veneer over old lake clays, as it does along the northeastern marginal zone. Clay is present beneath the alluvium west of the playa, as shown in washes which cut through the alluvium and expose the underlying lake clays. The upper few inches of these clays along the entire marginal zone tend to be puffy and soft, except in the washes. This condition can be attributed to surface runoff penetrating the upper zones of the playa and acting on clay whose slightly higher silt and sand content favors penetration of moisture, or to discharge from an artesian aquifer under the clays.

The lacustrine history of Coyote Playa is most clearly seen in the southern marginal zone. This zone is covered entirely by sediments associated with one of the last lacustrine phases of the area. The sediments were deposited as the area now occupied by the playa became an isolated body of water during the waning stages of Lake Manix (Hagar, 1966, p. 188). The southern margin of the playa is characterized by a slope of varying gradient. In the western sector of the margin, this slope is much steeper toward the top and becomes more gradual toward the base; but along the eastern sector, the entire slope is long and gradual. The playa slope

ranges in width from approximately 300 feet in the western portion to almost 1 mile at the southeastern corner. The top of the slope ranges in height from 6 to 45 feet above the playa surface. Along the steeper western portion, the surface of the slope is characterized by puffy ground which extends onto the adjacent playa floor in this area. In the eastern sector, surface conditions on the gradual slope are subject to change. The relationships exposed where the southern embankment was trenched show that the clay in the bottom of the trench lies several feet above the level of the playa and can be traced continuously into the clay at the surface of the playa. Hence, it is concluded that the upper clay of the playa surface is approximately the same age as the clay exposed in the embankment and is probably slightly older. The manner in which the lacustrine deposits terminate abruptly along much of the southern marginal zone suggests that some of them have been removed by deflation.

In summary, numerous relationships in the marginal zones demonstrate clearly that Coyote Playa is not aggrading, and that the most significant phase of deposition has been the extension of alluvial fans over old lake sediments. The clays in the marginal zones, like those on the playa itself, are sediments deposited in a perennial lake, and are not materials brought to the playa during ephemeral floodings.

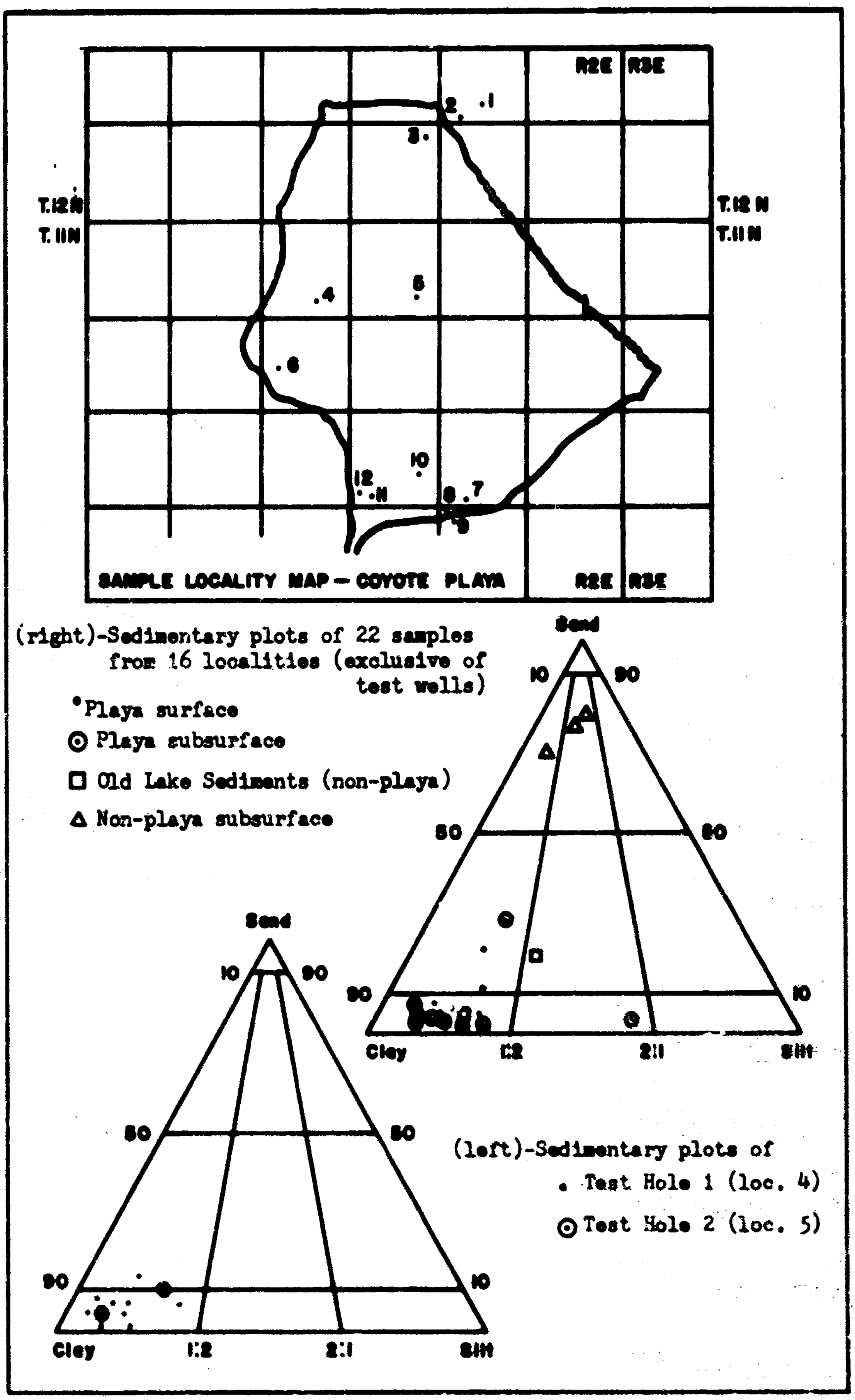

Figure 3. Sample location map and classification of selected samples (adapted from Hagar 1966, Figs. 5,6).

SUMMARY OF DATA OBTAINED FROM SAMPLES OF TEST HOLE 1 COYOTE LAKE, 1965

Depth (ft)	FIELD LOG	PERCENT MOISTURE	GSA ROCK COLOR CHART: COLOR	GSA ROCK COLOR CHART: NUMBER
0	Silt, brown, massive	---	Very pale orange	10 YR 8/2
	Silty clay, gray brown with CO_3 globules	14.49		
	Clay, gray brown with CO_3 laminations at 7 feet			
10	Limonite stains at 8 - 9 ft.	17.96	Mottled, gen. yellowish-gray with olive mottlings	5Y 7/2
		19.32		10Y 6/2
	Clay, gray brown with CO_3 globules and mica			
20	Arkosic sand and clay	3.28	Pale olive	10Y 6/2
	Clay, gray brown with CO_3 globules and mica flakes	16.96		
30		16.80	Light olive-gray	5Y 6/1
40	Clayey sand, fine grained	23.59	Light brownish gray alternating	5YR 6/1
	Clay, gray to brown with varves of fine sand and clay, CO_3 laminations (4 mm)	7.05	with pinkish-gray	5YR 8/1
50	Clay, gray with limonite streaks	32.85	Grayish olive	10Y 4/2
	Clay, gray-fine arkosic sand laminations	33.27		
60		25.73	Pale brown	5YR 5/2
	Clay, brown, massive	30.51		
70		34.82	Pale yellowish-brown	10YR 6/2
	Clay, grading from brown to gray	37.51		
80	(Note: same massive gray clay to 90 feet where drilling was terminated.)	26.60	Light olive-gray	5Y 6/1
		34.28	(some pale brown)	5YR 5/2
90		34.01	Dark greenish-gray	5 Y 4/1

Vertical scale 0.8" = 10'

Figure 4. Geologic log of Test Hole 1--sample locality 6 on Fig. 3. Field logs and soil moisture analyses obtained from David Carpenter and Ward S. Motts. (Adapted from Hager 1966, Table 4.)

Table 1: Summary of Sedimentary Analyses

Sample Locality	Depth in feet	PERCENTAGE Sand	Silt	Clay	Source of Sample
1	9	69.21	8.90	21.87	marginal zone
	14	76.89	9.60	13.50	" "
	25	82.07	11.52	6.37	" "
2	0	20.99	28.67	50.33	old lake sediments
3	0	21.04	16.21	62.39	playa surface
4	10	5.13	6.28	88.57	Test Hole 1
	20	7.03	13.71	79.76	" " "
	30	13.64	15.19	71.16	" " "
	40	4.43	14.11	81.45	" " "
	50	0.52	17.57	81.90	" " "
	60	7.10	7.03	85.86	" " "
	70	0.35	12.46	87.17	" " "
	80	5.86	25.65	68.48	" " "
	90	6.63	12.76	80.60	" " "
5	40	10.29	22.16	67.55	Test Hole 2
	60	3.12	12.26	84.62	" " "
6	6	2.46	16.04	81.49	playa subsurface western side
	12	3.60	11.35	86.00	"
	13	3.77	14.42	81.79	"
7	0	4.50	24.03	71.46	transitional surface puffy patch

Table 1: Summary of Sedimentary Analyses (cont'd)

Sample locality	Depth in feet	PERCENTAGE Sand	Silt	Clay	Source of Sample
	0.3	6.01	16.22	77.46	under puffy crust
	0	11.01	21.45	67.52	hard crust
	0.3	5.83	14.55	79.61	under hard crust
8	4	2.04	25.24	72.70	base of playa slope
	7.5	2.78	59.63	37.58	" " " "
9	0-3	4.12	20.35	75.52	southern embankment
10	0-1	7.19	12.63	80.16	uniformly puffy area
	1-1.2	7.82	6.88	85.29	" " "
	1.4	4.66	9.54	85.74	" " "
	2.0	5.11	14.85	80.03	" " "
	5.0	2.27	21.15	76.56	" " "
11	5.6	1.79	18.22	79.98	marginal zone, puffy area
	7.0	3.09	19.15	77.74	" " "
12	10.0	28.70	18.43	52.86	" " "

SEDIMENTOLOGY AND HYDROLOGY

Analyses of Sediments from Coyote Playa

Samples collected from the playa for analysis represent both the hard, compact surface, the soft, porous, puffy surface, and subsurface sediments beneath both types. Information concerning the subsurface stratigraphy of Coyote basin was obtained from deep drilling in the playa, shallow drilling in the playa and surrounding sediments, and logs of selected wells in the area.

A hand auger and a jeep-mounted, power auger were used by Hagar for shallow drilling which was restricted to depths of 18 feet and less on the playa itself because of the hardness of the clay. A rotary drilling and coring project was conducted on several southwestern playas in 1965 and 1966 in connection with the Air Force study of playas (Motts, Chap. 3, Pt. 2, and Motts and Carpenter, 1968). Coyote Playa was selected as the site for two test wells. From Test Hole 1 (sample site No. 4, Fig. 3) a core was obtained from 1 to 15 feet and 45 to 47 feet (Fig. 4). Coring was terminated at 47 feet because of the extreme hardness of the clay, and rotary augering was continued to a depth of 90 feet. Test Hole 2 (sample site no. 5) was drilled to a depth of 275 feet. The field logs of both test holes indicate that the playa is underlain by predominantly massive clays. Analysis of samples from Test Hole 1 to determine sand:silt:clay ratios shows that all the samples have a very high clay content, the highest being 89 percent in the sample collected at a depth of 10 feet (Fig. 4, Table 1). The average clay fraction for all samples from Test Hole 1 was 80.6 percent. Sediments obtained from an 18-foot hole in an area of hard surface and from an 8-foot hole in an area of puffy surface were also

fine-grained clays. The only coarse layers of significant thickness were a layer of clayey sand between 41 and 44 feet, reported in the field logs of both test holes. The second, a sandy zone occurring between 165 and 170 feet, penetrated sand:silt:clay ratio of 28.70:18.43:52.86. In contrast, analysis of a sample from an 8-foot hole near the southern marginal zone (sample loc. 8) showed that the material at a depth of 4 feet is a fine-grained, hard clay with a sand:silt:clay ratio of 2.04:25.24:72.70. Information on the sediments underlying the northeastern marginal zone is meagre, but Thompson (1929, p. 284) notes that a hole 73 feet deep near the contact between playa clays and overlying alluvial veneer in this area yielded no water. He describes the material on the dump pile near the hole as being "mostly a gray clay," so it is evident that this hole did not penetrate any coarser layers suggesting lateral interfingering with alluvium. Along the western marginal zone, however, wells penetrate more than one layer of water-bearing alluvium, and it is concluded that clays of the playa interfinger with coarse alluvial fan deposits. Presumably, a similar interfingering does occur along the northeastern marginal zone, but the extent of surface clays eastward under the alluvial veneer suggests that the contact at depth between clays and alluvium is east of the 73-foot hole described by Thompson.

The possibility that Lake Manix extended into Coyote basin was suggested by early researchers on Lake Manix (Buwalda, 1914; Blackwelder and Ellsworth, 1936). Hagar (1966) presented evidence to show that the area now occupied by Coyote Playa was once a large, northern embayment of the lake. Major currents from inlet to outlet in Lake Manix did not flow toward this embayment and only the finer sediments reached the Coyote basin, thus accounting for the very high percentage of clay-sized particles in the sediments of the playa.

Hydrology

The general objectives of the hydrologic phase of the study of Coyote Playa were: (1) an understanding of the relation of ground water in the basin to surface conditions on the playa, and (2) evidence on the relation of the playa to the ground-water divide and to the flow of ground water in the basin. A ground-water survey of wells from the Mojave River northward into Coyote valley was made by Hagar (1966), and this data was supplemented by information from Dyer and others (1963).

Results of the survey indicated that aquifers occur at several levels in the valley south of the playa owing to the presence of silts, sands, and gravels interbedded with layers of clay. Blue clay of unknown thickness is the basal layer in most wells. A probable ground-water divide was located between the Mojave River and the playa. North of this divide, ground water in the aquifers above the blue clay is flowing toward the playa, whereas ground water is flowing toward the Mojave River in the area south of the divide. To the west and north of Coyote Playa, ground water is under artesian head and is flowing toward the playa. Only a few wells are present in this vicinity, but available data on these wells indicate that at least two clay layers interfinger with coarse alluvium in the western marginal zone. Evidently fine-grained lake clays, extending shoreward in a tongue over older fan material, are acting as confining beds for water in the alluvium, and an artesian head results. Water may occur under artesian conditions on the northeastern side of the playa, but information is lacking because no wells exist in this area. In a 25-foot hole drilled during this investigation in the northeastern corner of the playa, the water table was reached at 17 feet in clayey sand, and after 15 minutes, water rose to the top of

the hole and overflowed. The approximate rate of flow was one gallon per 12 minutes.

A study of alluvial fans in the valley (Hagar, 1966, p. 146) and geologic mapping in the Alvord Mountain and Lane Mountain quadrangles by Byers (1960) and McCulloh (1952) indicate that Late Tertiary-Early Quaternary fan materials probably covered the area prior to the formation of Coyote basin and now underlie the playa at depth. If these fan materials extend to the Mojave River, it is possible that they serve as a deeper aquifer through which water drains from the valley. On this basis, Coyote valley is a topographically open, drained valley which, nevertheless, is similar to an open undrained valley, according to Snyder's (1962) hydrologic classification of valleys in the Great Basin. Considering the larger drainage basin of the Mojave River with which Coyote valley is associated, it is possible to classify Coyote Playa hydrologically as a "by-pass" type of playa (Motts, 1965, p. 81), since some of the ground water in the basin continues to a lower basin and does not discharge in the area of the playa.

Interpretations from Seismic Refraction Reconnaissance

In the summer of 1964, a seismic refraction reconnaissance was conducted at Coyote Playa by Mr. Gerry H. Cabaniss and Captain James T. Neal of the Cambridge Air Force Research Laboratories using a Geo-Space Corporation Model GT-2 seismograph with six geophones and a maximum spread of 350 feet. Eleven locations were tested on and immediately around Coyote Playa. From the information obtained and from topographic maps, cross-sections and profiles were drawn. One profile was oriented roughly west-east and the other north-south entirely across the playa.

A velocity of 6,900 ft./sec. obtained at 90 feet of depth from a shot point 2,000 feet north of the northern margin closely corresponds with the projected profile of wave-cut granitic fanglomerate north of the playa. A 7,000 ft./sec. velocity layer 40 feet west of the playa is best explained as either a buried pediment of a bedrock hill southwest of the playa or as a buried, partially indurated, wave-cut fanglomerate which may also be present west of the playa.

Below the playa surface, a velocity change from 1,300 to 4,300 ft./sec. at approximately 40 feet, undoubtedly represents the extensive sand layer (at 41 to 44 feet), encountered in both test holes. South of the playa, a 5,000 ft./sec. velocity layer closely corresponds with the measured depth to the water table in this area.

GEOLOGIC HISTORY OF COYOTE BASIN AND COYOTE PLAYA

Formation and Development of Coyote Basin

The following sequence of events is interpreted to have occurred in the formation and development of Coyote basin. (Also see Table 2.)

(1) Tertiary basin. Prior to the formation of the present Coyote basin, a large basin evidently extended from the Barstow syncline to the Alvord Mountain area and deposits accumulated from middle Miocene time until late Pliocene or early Pleistocene time (McCulloh, 1952, p. 173-174; Byers, 1960, p. 59-60). Drainage in the region during this time apparently was integrated (Byers, 1960, p. 60), and an ancestral Mojave River probably flowed through the area to the south along a course from the San Gabriel Mountains toward the Colorado River (Hewett, 1954, p. 19).

(2) Formation of Coyote basin. According to Byers (1960, p. 60), the Coyote Lake basin began to take form during the early to middle Pleistocene orogeny. Downward movement along the Coyote Lake fault resulted in the basin now occupied by the playa, and this movement was associated with the Alvord Mountain upwarp to the east. The granitic fanglomerate, deposited in the late Tertiary-early Quaternary basin, was tilted upward along the flanks of Alvord Mountain and remained exposed on the slopes north of Coyote Lake. Volcanic gravels, which may have been deposited in the older basin, also are interpreted as remnants of old fans; and as the floor of the basin dropped, these fans became isolated from their source (Byers, 1960, p. 42-43).

(3) Formation of Lake Manix basin. Middle Pleistocene movement along faults southeast of Troy Playa could have interrupted the drainage of the Mojave River so that a lake basin formed in the river valley west of the fault (Hewett, 1954, p. 19). This movement may have been contemporaneous with that which formed the Coyote basin to the north.

TABLE 2 - CHART OF PROPOSED SEQUENCE OF HISTORICAL EVENTS

Time	Climate	Lake Stages	Deposition	Erosion	Drainage	Deformation
Quaternary, Pleistocene, Late, post-pluvial	arid		dunes, sand sheet	yardangs (?)		
	semi-arid (?)	Coyote No. 2 (one or more stages ?)	sediments deposited by Coyote Wash	downcutting in Coyote Wash		
	arid		eolian sands, fans	deflation of playa and surrounding area		
Tioga		low level, Coyote No. 1		downcutting of Afton outlet	Mojave R. drains to Lake Mojave	
		Coyote No. 1	desert fluvial plain	meander scars	Mojave R. flows toward Afton basin	
			bay bars			
	humid	Manix No. 2	upper clays, Coyote L. Afton beach deposits	wave-cut benches	Mojave R. Flows from San Bernardino Mts. into Lake Manix thence through Ludlow-Bristol trough	
	arid		fan deposits			
Tahoe	humid	Manix No. 1	lower clays in Coyote basin; clays and beach deposits in Afton basin			
Early Middle	(?)					Manix and Coyote basins formed
	(?)		volcanic gravels			
Tertiary	semi-arid to subhumid		granitic fanglomerate		Mojave R. flows from San Gabriel Mts. to Colorado R. (?)	

(4) Initiation of Lake Manix. As soon as flow was established in the Mojave River, as a result of climatic conditions, a lake filled the basin. If the relative ages of the Lake Manix and Coyote basins are interpreted correctly, this lake probably extended northward into the Coyote embayment in an early stage of its development. The lack of evaporites in the sediments in the basin suggests that the lake remained relatively fresh, and therefore was drained by the Mojave River which continued to flow southeastward through the Ludlow-Bristol trough.

(5) Lake Manix No. 1. At least two lacustrine intervals, separated by a time of arid conditions, have been identified. The earlier lake, designated by Blackwelder and Ellsworth as Lake No. 1, was as much as 200 feet deep (Blackwelder and Ellsworth, 1936, p. 459), as indicated by the thickness of clays in Afton basin and the elevation of gravel bars. This lake, tentatively correlated with the Tahoe glaciation, eventually became dry as a result of arid conditions, and during this arid interval, fan material was deposited over the lacustrine deposits of Lake No. 1 in Afton basin. It is possible that fan materials extended over marginal clays in the Coyote basin at this time also, although information from wells in the marginal zones of Coyote Lake is too meagre to indicate the extent and depths of laterial interfingering of the lacustrine clays and fan material.

(6) Lake Manix No. 2. Evidence in Afton basin presented by Blackwelder and Ellsworth shows that there was a second lacustrine stage in the basin, and this stage is correlated tentatively with the Tioga glaciation. They show that the second lake filled the basin to a slightly higher level than Manix No. 1. This is substantiated by the existence of only one set

of wave-cut benches surrounding Coyote Lake. Any previously-existing shoreline features associated with the earlier lake presumably were destroyed by the later, higher lake. Two conditions might have been responsible for this higher level of Lake Manix during a time when lake levels in the Great Basin were generally lower*: (1) a relatively high rate of sedimentation in the lower Mojave valley was filling the basin, and although the lake was actually a shallower body of water, it rose to a higher level; and (2) additional movement along the same faults which originally interrupted the drainage of the Mojave River may have elevated the outlet, raising the level to which the lake could rise in the basin.

(7) Isolation of the Coyote embayment. Sediment gradually raised the floor of Lake Manix, by different amounts at different places, and eventually a bay bar was built which partially blocked the Coyote embayment. Later, coarser materials spread over the lake clays south and west of the bay bar, possibly in the form of a large delta from the Mojave River. As a result, that part of the lake in Coyote valley was isolated from the rest of the lake, and this lake is designated Coyote Lake No. 1. On the plain south of the lake, an aggrading, distributary stream from the area of the Mojave River shifted its channel, deposited additional amounts of coarse material, and broadened the area of fill separating the two lakes.

(8) Erosion of Afton Canyon. The Mojave River began to meander on the fluvial plain formed by the coarse deposits, but the river abandoned

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*It should be noted that, in general, Pleistocene lakes in the Great Basin attained their maximum depth and extent during the Tahoe glacial stage, and that the Tioga lakes were shallower and smaller (Morrison, 1965, p. 273). This has been established by studies of shoreline features and degrees of preservation of these features, suggesting that the higher ones are older (Blackwelder, 1931, 1946).

the meanders when it eroded the outlet south of Cave Mountain (Fig. 2) and cut Afton Canyon. The supply of water for Coyote Lake was greatly diminished, and the deposition of coarse materials in Coyote basin ceased. The level of Coyote Lake No. 1 probably dropped rapidly, and the lake became shallow, supplied only by local runoff. These events all may have occurred during Tioga time, since erosion of Afton Canyon and the association of the Mojave River with Lake Mojave (now Soda and Silver Lakes, Fig. 1, Chap. 1) probably involved a longer period of time than is represented by any post-Wisconsin pluvial.

(9) Post-pluvial, arid cycle activity. When the climate became arid after the Tioga glaciation, loose sands and silts in the area surrounding the playa were transported by eolian activity. Exposed near-shore deposits in the marginal area north of the playa were blown into dunes. Fine materials were blown from the inter-stream areas south of the playa also, forming dunes on the eastern side of the basin. The coarse materials on the surface in the southern marginal zone were sorted. Fine sands were winnowed out and deposited as dunes, while some of the coarser gravels were moved into pebble ripples. During this interval of arid climate, alluvial fans began to extend toward the playa surface, partially derived from materials supplied by erosion of older fans.

(10) Post-pluvial lacustrine stage. At least one interval within the last 10,000 years may have resulted in a minor lacustrine stage. The inferred lake in Coyote basin at this time is designated Coyote Lake No. 2. Coyote Wash was one of its major sources of inflow, and coarser materials now found near the mouth of the wash may have been deposited at this time. Dunes which had formed in the northern marginal zone became stabilized and somewhat in-

durated, probably by salts, calcium carbonate and fine clay particles combined with moisture.

(11) Return to arid climate. As soon as the desiccation of the lake occurred following the most recent pluvial, most sediments which may have been deposited in a shallow lake were removed by eolian activity, since they probably were coarser and less compacted than the older lacustrine clays which remained to form the present playa surface. Remaining coarser sediments at the mouth of Coyote Wash were eroded by intermittent activity of the wash. The slightly indurated dunes north of the playa were eroded by the wind into yardang topography as newer dunes formed adjacent to them. Dune building resumed in other areas surrounding the playa as well. The presence of the thin sheet of sand on alluvium east of the yardangs and the dunes on the Alvord Mountain bajada suggests that the most recent eolian activity post-dates the last major activity in the alluvial fans.

Geologic Age of Playa Sediments

The relationship of Coyote Lake to Lake Manix provides a basis for tentative dating of playa sediments and related features in the basin. However, so little study has been made of Lake Manix stratigraphy outside of Afton basin that it is extremely difficult to correlate any of the sediments in the Coyote basin with those in the lower Mojave valley or with the stratigraphy described by Blackwelder and Ellsworth (1936) in Afton Canyon. Accurate dating of sediments in the Coyote basin as well as in Afton Canyon is necessary before specific correlations can be made. Therefore, the ages suggested in this paper for the sediments in the playa and surrounding features are tentative, and correlations with stages of Lake Manix are those which appear most logical from a study of general geologic relationships.

As noted above, Manix No. 1 is tentatively correlated with the Tahoe (early Wisconsin) glaciation and Manix No. 2 with the Tioga (late Wisconsin) glaciation. Early and late Wisconsin lacustrine intervals have been established for other Pleistocene lakes in the Great Basin (Flint and Gale, 1958; Morrison, 1965), so it is logical to expect two lacustrine stages of these ages in Coyote basin with a stratigraphic break in the sediments representing an interlacustrial-interglacial interval. The clayey sand between 41 and 43 feet in depth is the most probable horizon beneath the surface of Coyote Lake known at present to represent the Tahoe-Tioga interglacial. If the clayey sand does represent this interglacial, then the clays below this horizon were deposited in Manix No. 1 and are Tahoe in age, and above this horizon the clays are associated with Manix No. 2 and are Tioga in age.

If these correlations are correct, the rate of Wisconsin sedimentation in Coyote basin and the lower Mojave valley was comparatively high. Although the total depth of clay beneath the playa is unknown, at least 47 feet of sediments of possible Tahoe age were penetrated by the 90-foot hole. Logs of wells in the central section of the lower Mojave valley indicate that blue clays are present to a depth of at least 350 feet below the surface. Accurate dating is necessary before it can be established that the deepest clays in the lower Mojave valley are late Pleistocene. The main basis for this at present is that the formation of the basin has been associated with the middle Pleistocene orogeny (Hewett, 1954 , p. 19).

In contrast to the 40 feet of possible Tioga sediments in Coyote Lake, the parting mud in Searles Lake is only 10 to 13 feet thick. The age of this mud has been determined by radiocarbon dating (Flint and Gale, 1958) to be late Wisconsin, and it is tentatively correlated with the Tioga glaciation.

The bottom mud is approximately 100 feet thick, and Flint and Gale correlate it with the Tahoe glaciation on the basis of radiocarbon dates. Although there are two deep salt bodies in Searles Lake which account for a considerable thickness of the deposits there, the total clastic sedimentation known to represent the Wisconsin glacial intervals appears to be considerably less than clastic sedimentation in Lake Manix tentatively associated with the same glaciations. The greater rate of sedimentation in Lake Manix is quite possible, since the Mojave River did not flow through any major basins upstream from Lake Manix (Thompson, 1929; Blackwelder, 1954). This lake was once the principal settling basin for sediment carried in the upper section of the river. In contrast, the Owens River connected two large lakes upstream from Searles Lake--Owens Lake and China Lake (Blackwelder, 1954); and these lakes undoubtedly received significant amounts of the clastic sediment carried by the Owens River during the Pleistocene humid episodes.

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CHAPTER 3, PART 2: RESULTS OF TEST-DRILLING AND WINTER MAPPING PROGRAMS ON COYOTE PLAYA, CALIFORNIA

Ward S. Motts

INTRODUCTION

As part of the reconnaissance phase of this investigation, the author first visited Coyote Playa and other playas in western United States during the summer of 1962. It was apparent that Coyote Playa had many geomorphic and sedimentary features worthy of detailed study, including a more diversified surface morphology than most fine-grained playas of western United States; therefore, it was decided that Coyote Playa should be one of the first playas studied in this investigation. The subsequent detailed study by Hagar (1966 and Chap. 3, Part 1) has added greatly to the understanding of the geology of Coyote Valley, especially about the relation of playa deposits to the surrounding geomorphic features. Hagar noted the low moisture content and hard character of the extremely fine-grained playa clays. He concluded that except in some marginal areas, an insignificant amount of ground water discharged through the playa surface and that it's varied surface morphology was due primarily to the interaction of infiltrated surface water with playa sediments.

In order to learn more about the sediments and the geomorphic processes operative on Coyote Playa, the author, assisted by David Carpenter, conducted a rotary drilling and coring program in 1965 and 1966 on Coyote Playa as part of a broader drilling program on several playas in the Mojave Desert. Some of the findings from this rotary drilling program are published in Motts and Carpenter (1968). Also during 1967-68, the author visited Coyote Playa

for further study and mapping during the winter in order to supplement the work of Hagar which had been done during the summer months.

The data obtained from the drilling and mapping programs substantiated Hagar's conclusions that the sediments of Coyote Playa are very fine grained and poorly permeable. However, Motts concludes that throughout the playa surface, capillary discharge of ground water occurs from a shallow (10 to 25 foot) extensive zone of subsurface permeability, and capillary discharge combined with hydrostatic head occurs from deeper water-bearing beds below the playa clays. This capillary discharge may have an important influence on the surface morphology for reasons discussed in this article. It is hoped that further detailed studies will assess the relative significance of the processes related to surficial water discussed by Hagar (Chap. 3, Part 1) and the ground-water processes discussed in this chapter on the development of surface morphology of Coyote Playa.

DEEP DRILLING PROGRAMS, 1965 AND 1966

In 1965, Test Hole 1 was drilled about 4,000 feet from the northwest margin of the playa (Fig. 1). Core was obtained from 1 to 15 feet and from 45 to 47 feet; samples were taken every 10 feet. Coring was discontinued at 47 feet because of the difficulty of penetrating hard clay; rotary augering was continued to 90 feet, which was the total depth of the hole. Field examination of sediments from Test Hole 1 (Chap. 3, Pt. 1, Fig. 4) shows plastic clays interbedded with thin units of fine-grained arkosic sand. The thickest sand bed was penetrated from 41 to 44 feet; other thin sand laminations occurred at depths of 12, 20, and 57 feet. Clay with carbonate laminations occurred at several depths. Dry clay at the surface graded into clay containing a moisture content of 15% at 5 feet and 34% at 85 feet. Soil moisture content down hole fluctuated; abrupt decreases in soil-moisture occurred within or near sand layers at the 20 and 40 foot depths.

Test Hole 2, drilled near the center of Coyote Playa, penetrated 204 feet of clay and silty clay interbedded with minor amounts of sand and silt (Figs. 1 and 2). Continuous cores were taken from 0 to 115 feet and from 165 to 175 feet. The hole was rotary drilled from 115 to 165 feet and from 175 feet to the bottom of the hole; field inspection of the cuttings was made as they came to the surface in the circulating muds. Highly plastic and moist clays were encountered throughout the length of the core with the exception of dry clays in the upper foot. Samples were taken from the center of the core for sedimentary study and soil moisture analysis. Inspection of the clay cores showed that there was little to no penetration of circulating mud into the cores because of the dense, poorly permeable nature of the playa clay and because of the short time that the circulating mud was in

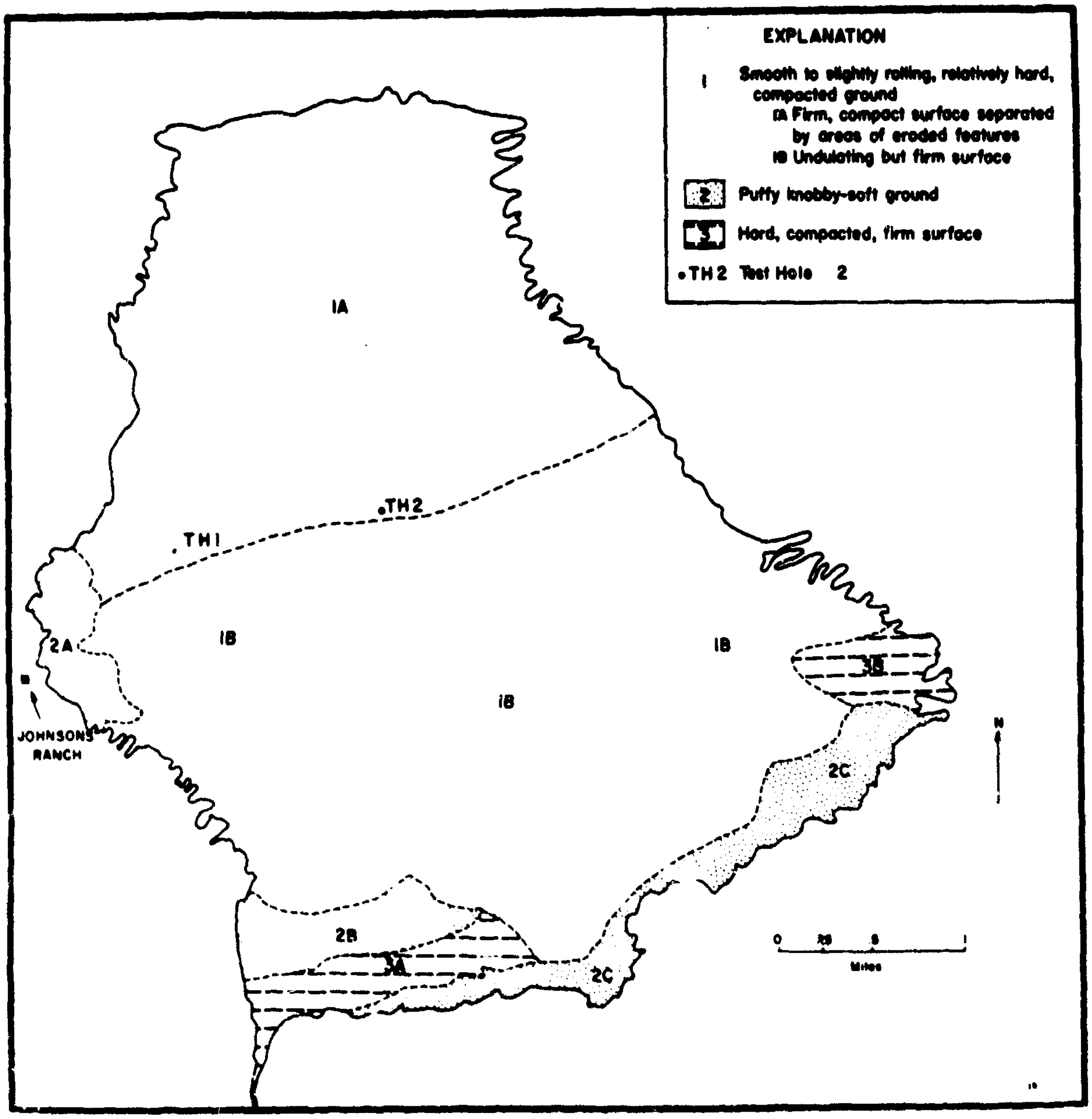
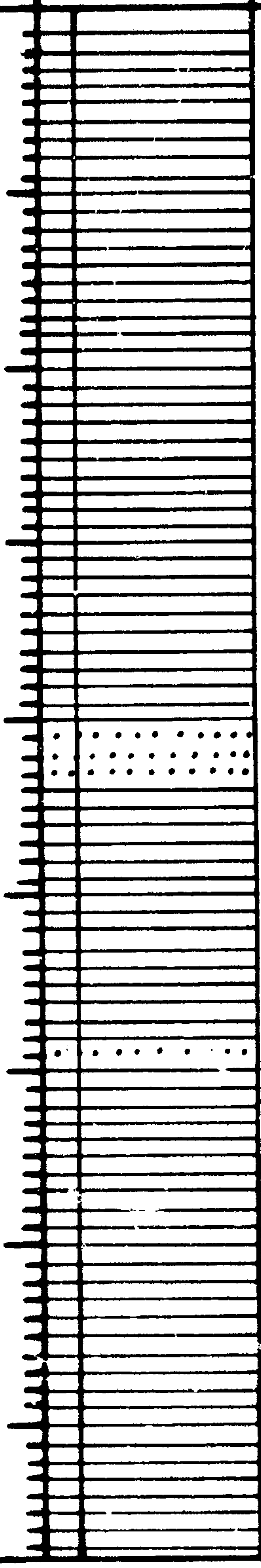


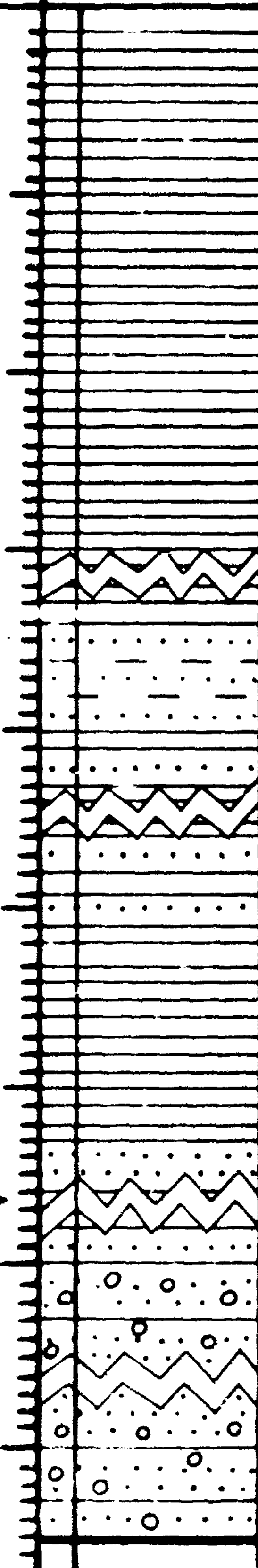
Figure 1. Playa surface types of Coyote Playa, winter 1967-68, and location of deep test holes. (Mapped by Motts.)

Hydrologic		Depth	Log
2.44	sur		
16.12	1		
18.12	2		
18.48	5		
		10	
25.54	16		
27.94	20	20	
29.05	24		
31.53	25		
37.56	30	30	
27.72	40	40	
32.04	50	50	
35.71	54		
34.93	60	60	
31.79	70	70	
36.00	80	80	
32.46	84		



Description	
0 - 11	Clay, very pale orange 10 YR 8/2 to moderate brown 5 YR 4/4, dry to slightly moist.
11 - 16	Clay, pale olive 10 Y 6/2, moist, plastic.
16 - 20	Clay, pale yellowish brown 10 YR 6/2 and moderate yellowish brown 10 YR 5/4, moist, moderate to good plasticity.
20 - 21	Clay, pale olive 10 Y 6/2 to light olive gray 5 Y 5/2.
21 - 26	Clay, light olive gray 5 Y 5/2 to light olive brown 5 YR 6/2
26 - 41	Clay, dark yellowish brown 10 YR 4/2, moist, plastic.
41 - 44	Sand.
44 - 55	Clay, dark yellowish brown 10 YR 4/2, moist, plastic.
55 - 59	Clay, light olive gray 5 Y 5/2, moist, plastic.
59 - 60	Sand, clayey, light olive gray 5 Y 5/2.
60 - 62	Clay, moderate brown 5 YR 6/4, moist, plastic.
62 - 64	Clay, light olive gray 5 Y 5/2, moist, plastic.
64 - 70	Clay, medium bluish gray 5 B 5/1, moist, moderate plasticity.
70 - 74	Clay, dark gray N3, moist, plastic.
74 - 79	Clay, light olive gray 5 Y 5/2, moist, plastic.
79 - 87	Clay, dark yellowish brown 10 YR 4/2, moist, plastic.

Figure 2. Geologic log and soil moisture content for Coyote Test Hole 2, SW 1/4, SE 1/4, sec. 3, T. 11 N., R. 2 E.

Hydrologic		Depth	Log	Description
34.71	67.5			
		90		93 -107 Clay, pale yellowish brown 10 YR 6/2 to grayish blue green 5 BG 5/2.
37.47	96			107-114 Clay, pale green 10 G 6/2, moist, plastic.
		110		
39.76	114			114-165 Clay, mostly light blue and green, moist, plastic.
		120		
[illegible].50 ?	165			165-170 Sand and silt, very fine grained
[illegible].72	170	170		170-189 Clay, sandy, moderate brown 5 YR 3/4, interbedded with sand, medium grained.
[illegible]1.38	175			
				189-191 Clay, sandy, light olive gray 5 Y 6/1, moist, plastic.
		190		191-204 Clay, medium bluish gray 5 B 5/1, massive, moist, plastic.
		200		
				204-230 Sand, clayey, medium bluish gray 5 B 5/1.
water zone →				
		230		230-275 Sand and gravel, silty and clayey, with evidence of boulders 1 ft. in diameter at 240 ft.
		270		
				275 Bottom of test hole.

contact with the clay. Large clay chips collected from the circulating mud also indicated moist plastic clay; there was no apparent penetration of circulating mud into the centers of the chips. The fine-grained and highly plastic clay was predominantly olive, light brown, and gray in the upper hundred feet of the hole; predominantly green and blue from 100 to 165 feet; and predominantly brown and olive gray from 165 feet to the bottom of the hole. The sequence of brown and gray clays in the upper part of the hole, and green and blue in the lower part of the hole is similar to the general sequence observed at Rosamond Playa. The blue and green clays may have been deposited under reducing conditions in deep water and the brown clays deposited under more oxidizing conditions in shallow water, similar to the color origin of clays proposed by Motts and Carpenter (1968, p. 47) for Rosamond Playa. From 170-189 feet, the clay was interbedded with sand as alternating beds suggesting a varve type of deposition. The very fine-grained and highly plastic nature of the clays extending from the surface to the bottom of the hole is strong supplementary evidence that these sediments of Coyote Playa were deposited in a lake environment and support similar views by Hagar (1966, p. 193-196).

Laboratory analyses of a representative clay sample from Test Hole 2 at 60 foot depth showed 3 percent sand, 12 percent silt, and 85 percent clay; a sample from 40 foot depth just above a prominent sand bed had 10 percent sand, 22 percent silt, and 68 percent clay. Beds of sand were intercalated in the clays of Test Hole 2. The thickest sand beds occurred from 41 to 44 feet and from 165 to 170 feet. A thin layer of sand about 1 foot thick was penetrated at 59 feet, and several sand layers were encountered from 170 to 204 feet. Some of the well-sorted and fine-grained sand may be of

eolian origin. Hagar (1966, p. 210) proposed that the sand unit from 41 to 44 feet encountered in Test Holes 1 and 2 may have been deposited in the interpluvial between the Tahoe and Tioga glaciations because the thickness (158 feet) of the lower clays in relation to that of the upper clays (44 feet) is consistent with relationships to other lake clays in the Great Basin where reports indicate that deposition during the Tahoe glaciation was proportionately greater than during the Tioga glaciation (see also Chap. 3, Pt. 1, p. 102-104).

From 204 to 275 feet, Test Hole 2 penetrated artesian water in sands, gravel, and fanglomerate. The water rose to a height of 20 feet above the playa surface and flowed uniformly at a rate of about 100 gallons per minute. The water was slightly saline; the Department of Water Resources, State of California, analyzed the water as having 2,403 ppm total dissolved solids of which 865 ppm were chlorides and 352 ppm were sulfates.

The soil-moisture content of Test Hole 2 (Fig. 2) abruptly increased from 2.4 percent at the surface to 16 percent at a depth of 1 foot and further increased to about 26 percent between 5 and 16 feet. The soil-moisture content increased to a maximum of 40 percent at a depth of 114 feet. Down the hole, minor fluctuations were noted in moisture content which were probably related to differences in grain size. For reasons discussed in the next section, this author believes that the abrupt increase of moisture at shallow depths and the general increase of moisture in fine-grained sediments down hole are evidence that discharge by ground water is occurring at the playa surface.

Hydrologic characteristics of the sand bed from 41-44 feet influence the amount of ground-water discharge through the playa surface. Only small

amounts of water can percolate upward if the sand bed is unsaturated throughout the playa. Conversely, large amounts of water can move upward only if the sand is saturated and water is in contact with the upper and lower clay boundary. Unfortunately, the test drilling programs of 1965 and 1966 did not yield sufficient data to satisfactorily determine which of the above two conditions is correct. Field observations of the core at Test Hole 1 suggested that the sand was not saturated and significant amounts of water did not discharge from the sand bed as drilling progressed down hole. At Test Hole 2 the sand slipped through the core, indicating only an uncohesive condition of the sand. A rotary drill rig with circulating mud was used, and small amounts of water could have discharged into the hole from the sand bed without notice. The author believes that the permeability of the sand bed is probably very low and only small amounts of water move through it. The sand bed is probably highly silty and clayey in places because it was deposited in a lake where continuous sedimentation of clay and silt occurred. Future drilling should determine the hydrologic characteristics of the sand and also determine if a continuous sand bed is present or a "sand zone" in which sand interfingers laterally with sandy clay and silt. The pattern of this interfingering may have a significant influence on the hydrology of Coyote Playa.

MAPPING OF COYOTE PLAYA SURFACE, WINTER 1967-68

The author mapped the surface of Coyote Playa during the winter of 1967-68 following heavy rainfall and extensive flooding in early November 1967 (Fig. 1). The playa surface that winter could be differentiated into three major surface types and mappable units which were given the following numerical designations: Type 1 was characterized by a surface ranging from smooth to slightly rolling, and occupied the greatest area of the playa; Type 2 was a puffy surface occurring in the western, the southwestern and the southern part of the playa; Type 3 was a relatively smooth and hard surface found along Coyote Wash and along a large wash entering the playa from the southeast. Types 1 and 3 are probably equivalent to Hagar's hard compact surface, and Type 2 is equivalent to his puffy surface.

The entire Type 1 surface was relatively smooth and could be crossed by automobile with little difficulty; however, there were two major subtypes: (1a) a large area of firm, compact surface in the central and northern part of the playa, and (1b) a wavy, undulating surface in the central and southern part of the playa. Subtype 1a occupied most of the playa and extended northward from an imaginary east-west line through Test Hole 2 (Fig. 1). Subtype 1a was a dry, compact surface characterized by smooth, hard areas that ranged in size from 5 to 50 feet in diameter. The playa surface between the smooth areas consisted of etched and eroded polygonal cracks that were deeply incised from sheet wash (Fig. 3). In some cases the depth of erosion was as much as 2 inches. Commonly, the etched polygons occurred on broad swells that were raised above the surface of the smooth playa to a height ranging from a few inches to more than a foot and a half. In places the surface type just described graded into a

Figure 3. Type 1a surface northwest of Test Hole 2. Relatively smooth areas separated by areas of surficial fractures, eroded by sheet wash.

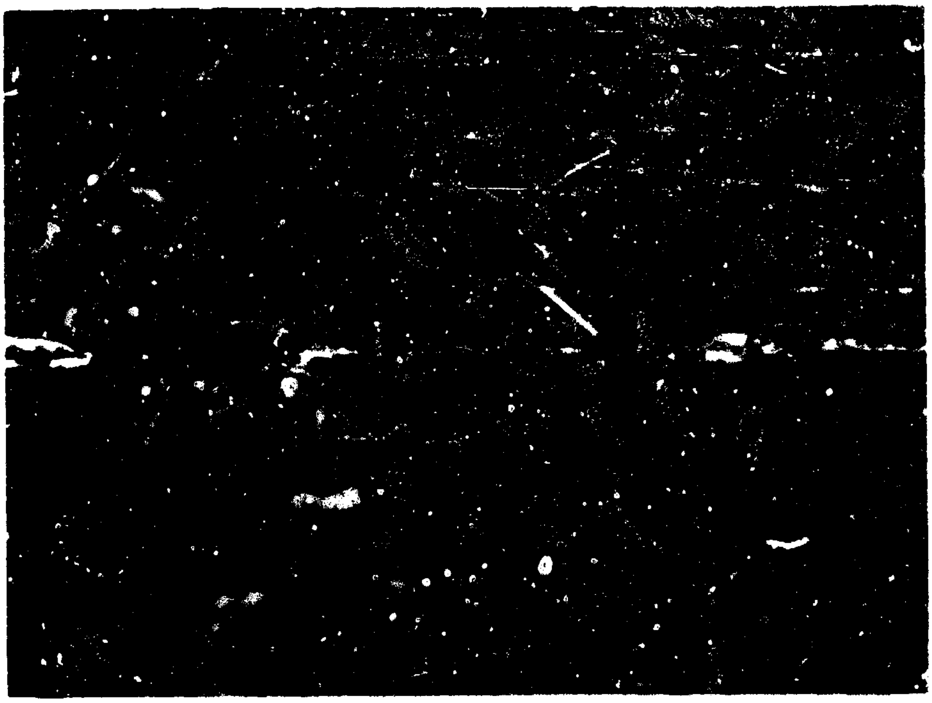


Figure 4. Type 1b surface showing uplifted side of newly formed fracture. May be evidence of "heaving action" from deposition of salt accompanied by capillary discharge through the playa surface.

surface consisting of "cobblestone polygons" (Hagar, 1966, p. 49). Another variation of subtype 1a near the Johnson Ranch (Fig. 1) was a very smooth surface characterized by a shiny glaze probably due to clays deposited with their long axes parallel to the playa surface.

The subtype 1b surface occurred south of an approximate east-west line through Test Hole 2. Numerous polygonal fractures were superimposed on this wavy, undulating surface. Three "orders of distortion" could be recognized on the surface. The first order consisted of gentle swells or mounds ranging from 20 to 30 feet across and several hundred feet in length. Upon these were superimposed a second order of gentle mounds which were about 5 feet wide and 10 to 15 feet long. The third order consisted of small mounds about 1 foot in diameter. The entire surface was highly irregular and contained many pits and depressions as well as numerous polygonal cracks.

Following test drilling of Test Hole 2, the author unexpectedly obtained evidence that, in the area of the test hole, a zone of very shallow permeability (2-5 inches deep) was present below the 1a surface. To avoid confusion with the subsurface system of shallow permeability (10 to 25 foot depth) this 2 to 5 inch zone is herein called the near-surface zone of permeability. This zone of permeability may be present throughout other parts of the Type 1 surface and may be part of the same zone of near-surface permeability that Hagar (1966, p. 61) describes as formed by weathering and flaking of clays. After Test Well 2 had been flowing for several hours, an attempt was made to park a truck fairly close to the well in an area of seemingly hard, compact surface. However, the truck was badly mired in soft wet clay at a depth of about 5

inches below the surficial dry clays. Water had moved laterally through the near-surface zone from the test well. The occurrence of this near-surface zone below the hard compact 1a surface suggested to the author the possibility that desiccation of the playa clays may be accompanied by processes of horizontal fracturing similar to sheeting in sedimentary and crystalline rocks.

The puffy ground of Type 2 may be divided into subtypes (2a) near Johnson's Ranch (Fig. 1) on the west side of the playa, (2b) north of Coyote Wash corresponding to Hagar's puffy ground not associated with ground-water discharge, and (2c) a band of puffy ground along the southern margin of the playa corresponding to Hagar's puffy ground associated with ground-water discharge. Subtype 2a was characterized by microrelief ranging from about 1/2 to 3 inches; much of the surface was white with halite stain. Small washes were incised into the surface to a depth of almost 1-1/2 feet. The surface had numerous small knobs ranging from about 1/2 inch to 4 inches across, and from 1/4 inch to 2 inches high. Small holes, several inches deep, were interspersed on the surface between the knobs. The marginal zone of the desert flat adjacent to subtype 2a was also characterized by puffy ground.

The subtype 2b surface near Coyote Wash had microrelief from 1 to 4 inches. The surface had brownish nodular masses ranging from 1/2 to 2 inches across. Halite was not present on the high nodular areas, thereby giving the entire surface a "pimpled" appearance. Numerous pits extended several inches into the subsurface; they ranged from a fraction of an inch to about 2 inches across. The entire 2b surface was highly friable and broken by fractures and cracks.

Subtype 2c occurred as a band along the southern margin of the playa. Hagar (Chap. 3, Pt. 1, p. 76) concluded that this band of puffy ground was formed from highly mineralized ground water seeping onto the playa clays from a sand bed that is exposed in the escarpment, bordering the south rim of the playa. This surface had a microrelief ranging from about 1/8 to 1-1/2 inches; large parts of the surface were relatively smooth. Much of the surface was covered with a coat of white salt crust including halite. Throughout the southeastern part of the band, the puffy ground had a microrelief of about 1 inch. Some areas of puffy ground along the southeast margin of the playa occurred about 10 feet above the lower playa surface and appeared to be a relic surface from a time of greater ground-water seepage.

The Type 3 surface consisted of relatively smooth hard ground in the southeastern part of the playa and in the southwestern part where Coyote Wash enters the playa. Much of the smooth, hard surface had a microrelief of less than 1/2 inch. The smooth areas were dissected by the sinuous drainage pattern of Coyote Wash. Parts of Type 3 surface were also covered by relatively numerous xerophytes and abundant sand and gravel. Some areas of the surface had numerous small pits that ranged in diameter from about 1/8 inch to more than 2-1/2 inches. These pits at one time contained sand and gravel that were later removed as the result of flooding (see also Motts, Chap. 7, p. 267).

INTERPRETATIONS

Data from the test hole drilling programs and field work led the author to make the following interpretations concerning the geology and hydrology of Coyote Playa. (1) The playa has a large interconnected zone of shallow subsurface permeability, 10 to 25 feet deep, that may be considerably more extensive than the surface expression of giant desiccation polygons. (2) Ground water is discharging through the playa surface by capillarity from the shallow permeability system described above, and by capillarity combined with hydrostatic head from a deeper artesian aquifer in sand and gravel below the playa clays. (3) Some features of the playa surface, including puffy ground and the wavy undulating surface, may be formed wholly or in part from processes associated with ground-water discharge.

Extensive Zone of Subsurface Permeability

Information obtained from the winter mapping program suggests that Coyote Playa is underlain by an extensive zone of subsurface permeability 10 to 25 feet deep that is related to the occurrence of giant desiccation polygons. Neal, Langer, and Kerr (1968, p. 72) state that the entire surface of Coyote Playa is fissured with giant polygons ranging in size from 30 to 75 meters. Lachenbruch in Neal, Langer, and Kerr (p. 83) explains that the fissure spacing (polygon width) is generally about 10 times the fissure depth, suggesting that the depths of fractures in Coyote Playa range from about 3 to 7.5 meters or in the order of 10 to 25 feet.

Rapid infiltration of surface water from a major storm into the subsurface fracture system in the winter of 1967-68 and the occurrence of

salt-encrusted puffy ground throughout the playa surface observed after this storm, indicate that the zone of subsurface permeability may be considerably more extensive than had hitherto been realized. Coyote Playa and Rosamond Playa were both flooded to the same approximate depth by the extensive and heavy storm in November 1967. Water drained from Coyote Playa two weeks after the storm, whereas water remained on Rosamond Playa until late March 1968. Water on Coyote Playa immediately drained into the extensive fracture system; whereas, the unfractured Rosamond Playa remained almost impermeable to downward movement of water. It is significant that Rosamond Playa, like Coyote Playa, is characterized by sediments of very fine-grained texture with a large clay fraction.

Following the flooding of Coyote Playa, salt-encrusted ground was found not only along many giant polygons but also scattered at random between the polygons, suggesting that water entered the polygonal fissures, moved laterally away from them along zones of interconnected porosity, and returned to the surface by capillarity. Numerous areas of salt-encrusted ground, scattered rather evenly throughout large areas of the playa surface in the vicinity of Test Hole 2, may have been formed by up-hole artesian leakage of water into the zone of subsurface permeability as discussed in the section "Capillary Discharge of Water Through the Playa Surface."

At Coyote Playa, Mr. A. Dutcher, U. S. Geological Survey (oral communication) has observed large quantities of water flowing into fissure cavities which form at the intersection of giant desiccation polygons, Similar observations have been reported by local residents, some of whom report a "whirlpool effect" as water pours into these cavities. Hagar (1966, Pl. 12C) described and photographed drainage channels leading into

the fissure cavities, indicating that water approached the cavities with erosive velocity.

It is noteworthy that a similar zone of shallow permeability more extensive than the surface expression of giant desiccation polygons has been found on North Panamint Playa, California, which, like Coyote Playa, is in an advanced stage of giant polygonal fracturing. Two test wells drilled in the central and northern parts of North Panamint Playa encountered high porosity zones at depths of about 25 feet. At both holes drilling operations had to cease at the 25-foot depth because of extensive loss of circulating mud (Motts and Carpenter, 1968, p. 44). There was no surface expression of giant desiccation polygons near either test hole.

It is interesting to speculate about some possible origins of the shallow permeability zone. The subsurface channels away from the present giant desiccation polygons may have been formed by ancient giant polygons whose fissures have been closed or "healed", thus preserving the subsurface cavities. Motts (Chap. 7, p. 262) discusses mechanisms of sediment flow by which surface fractures of fine-grained playas may be healed. The buried permeability zones may be kept open by periodic movement of large volumes of ground water derived from playa flooding. This process of subsurface erosion and flushing by ground water is known as "piping." Philip Durgin (manuscript in preparation) believes that ground-water piping is an important process in the development of giant desiccation polygons at North Panamint Playa. Perhaps desiccation of hard, compact playa clays is accompanied by horizontal and parallel fracturing in parts of the playa somewhat similar to sheeting in some sedimentary and crystalline rocks. Future studies should seek more information on the occurrence and origin of the zone of

subsurface permeability which may have a significant influence on the geomorphic evolution of many fine-grained playas.

Discharge of Ground Water Through Playa Surface

In this section hydrologic and geologic evidence is presented showing that ground water discharges through the surface of Coyote Playa. While writing this report the author learned that William Hart, U. S. Geological Survey (personal communication) has independently reached a similar conclusion that ground-water discharge is occurring through the surface of Coyote Playa, and he has estimated that the amount of annual discharge is about 500 acre-feet (manuscript in preparation).

Hydrologic Evidence

A well defined moisture-potential gradient between the less-saturated clays near the surface and the higher-saturated clays deeper in the playa provides the best evidence that ground water is moving upward through the playa sediments (Fig. 2). The lower moisture content at and near the surface is probably due to continuous evaporation of discharging ground water. Data from Test Hole 1 (Chap. 3, Pt. 1, Fig. 4) shows an irregular increase of soil moisture in the fine-grained sediments from 15 percent at 5 foot depth to 34 percent at 90 foot depth. Data from Test Hole 2 (Fig. 2) shows an abrupt increase of soil moisture from 2.49 percent at the surface to 16.12 percent at 1 foot, and an increase of the soil moisture content down hole in the fine-grained sediments.

If ground water were not discharging from depth, one would expect a "core" of desiccated clay characterized by a very low moisture content

rather than the moisture profile shown in Fig. 2. The core would be underlain and overlain by clays with a much higher moisture content. The higher moisture content in clays near the surface would be caused by infiltration of water from playa floodings, whereas the higher moisture content in clays at depth would be caused by capillarity from the artesian aquifers of sand and gravel underlying the clays. It is reasonable that such a deep-seated desiccation profile would develop because a playa rather than a lake has been in existence for a long time at Coyote (possibly thousands of years). However, drilling at Test Hole 2 encountered no highly desiccated core.

At a depth of 204 feet in Test Hole 2 artesian water was penetrated in sand and gravel below very plastic, fine-grained clays, and rose in the hole to 20 feet above the playa surface. This head, high above the playa surface, combined with strong capillary forces of the fine-grained sediments, supplies the hydrostatic potential necessary to force water upward through the sediments. That ground water can and does move through very fine-grained clastic sediments has been demonstrated in numerous hydrogeological studies, including Todd (1959), Yoder (1955), and Bredehoeft and others (1963). Clay-size sediments offer resistance to upward movement of water as shown by lower head drops in successively shallower sediments. However, upward movement of water through very fine-grained sediments is aided by capillary processes, and possibly also by other hydrostatic mechanisms peculiar to clay and fine silt that have had little study (B. Workington, Soils Physicist, oral communication).

A slight increase in moisture content of the upper 30 feet of clays in Test Hole 2 may be caused by surface water infiltrating into the 10 to 25 foot zone of subsurface permeability. Moisture content in Test Hole 2

increased from 1 to 30 feet, slightly decreased from 30 to 96 feet, and increased again at greater depth. The shallow moisture content may be caused by (1) direct infiltration of water through the surface and surface fractures in the upper few feet of the playa or more likely by (2) infiltration through giant polygonal fissures becoming shallow perched ground water in the zone of subsurface permeability. Part of this perched ground water increases the moisture content of surficial clays by capillarity in lateral directions and part probably discharges directly through the surface by capillarity.

Geological Evidence

The following geological phenomena indicate that ground water discharges through the surface of Coyote Playa: uplift, puffy ground, and salt-encrusted ground along polygonal fractures; large areas of wavy surface and broad swells; small areas of salt-encrusted ground scattered throughout the playa surface and along topographic high areas; and numerous areas of salt-encrusted ground around Test Hole 2.

(1) Uplift has occurred along the margins of numerous polygonal fractures (Figs. 4 and 5). Capillary discharge accompanied by deposition of salt along the fractures causes an increased volume of sediments which in turn results in uplift (see Chap. 7, p. 247). Salt deposition and volume expansion are probably also responsible for puffy ground along some of the fractures (Fig. 5).

(2) Processes similar to the above may have caused the broad earth "swells" of Type 1 surface described in a previous section. An alternate view is that the broad swells were caused by playa clays absorbing surface water which penetrated the surface. However, in other fine-grained playas

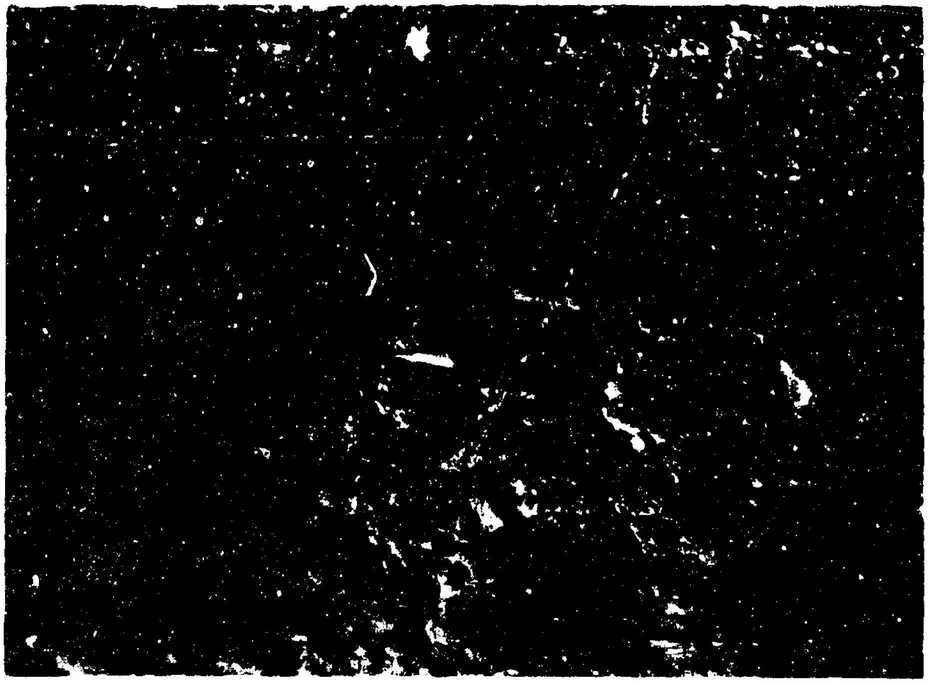


Figure 5. Freshly formed surficial fracture showing puffy ground along crack, and upturned edges on both sides of cracks, two evidences of capillary deposition.

Figure 6. White, salt-encrusted ground deposited by capillary discharge along giant desiccation polygons in south-central part of playa.

studied by the author (Rogers, Rosamond, Big Smoky and North Panamint), surface water tended to compact and smooth out the surface rather than produce irregularities as seen on Coyote.

(3) One of the best indications of capillarity through the surface of Coyote Playa during the winter of 1967-68 was the numerous white, salt-encrusted areas, many of which occurred on topographically high areas. The small irregular areas were a few feet in diameter and in most places underlain by friable puffy ground. Some of the puffy ground contained fine-grained crystals of salt; the formation of salt probably disrupted the playa sediments and helped cause the granular texture. Some areas appeared to be controlled by fractures and cracks on the playa surface, whereas other areas did not have any such observable control. Some salt areas may have been deposited by surface water which dissolved, transported, and later deposited the salt in isolated pools. However, salt-encrusted puffy areas along the higher parts of giant desiccation polygons (Fig. 6) and of smaller cracks (Fig. 7) indicate that these areas of salt were formed by capillary discharge. The higher salt areas are difficult to explain by surface water deposition, because the salt would precipitate out of solution in topographically low areas.

An alternate view is that flood water infiltrated a few inches into the shallow playa sediments, moved laterally, and later emerged at the surface by capillarity to form the salt-encrusted areas. Some areas may have been formed in this way; however, it seems questionable whether only water of surficial origin could have produced the numerous salt-encrusted areas widespread on Coyote Playa. Flood water contains only small concentrations of dissolved salts; whereas, ground water contains much larger concentrations

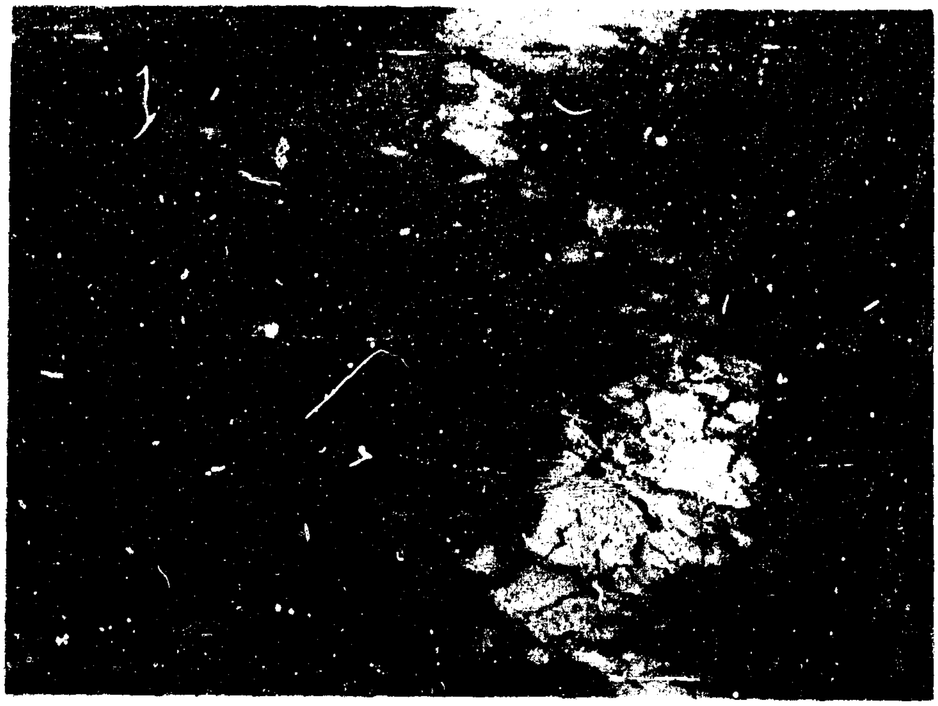


Figure 7. White, salt-stained area along uplifted fracture on Type 1 surface. Salt was deposited by capillary discharge through fracture. Surface-deposited salt occurs in topographically low, not high, areas.

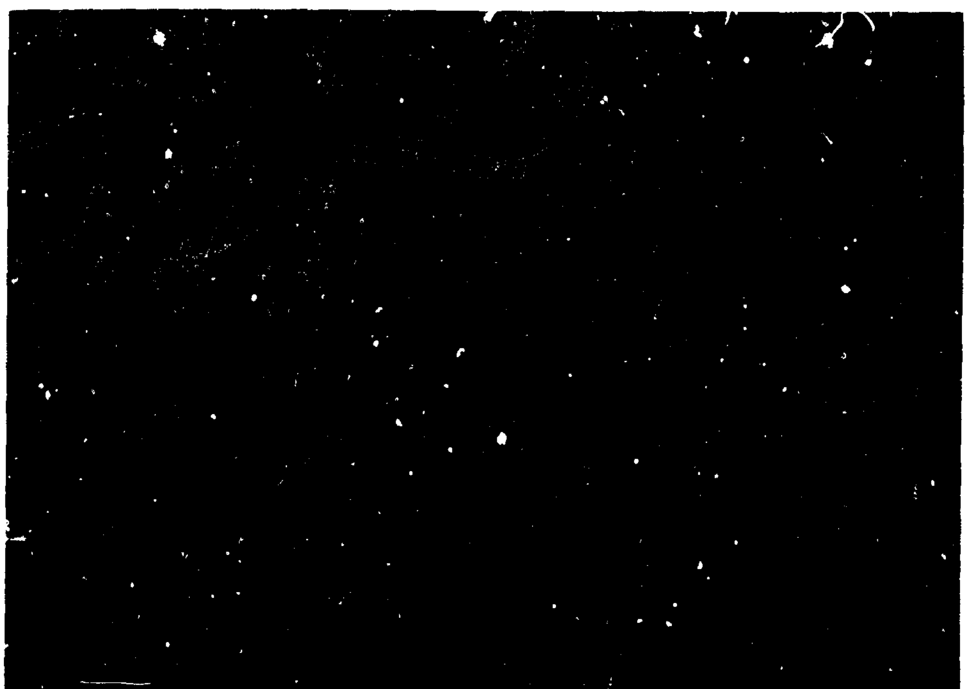


Figure 8. Numerous patches of salt-stained ground underlain by puffy ground in vicinity of Test Hole 2. In the winter of 1967-68, these patches occurred on most parts of the playa surface, but they were especially abundant in the vicinity of Test Hole 2.

of salt taken into solution as the water slowly moves through the crust of the earth. Processes of ground water solution and deposition appear to be the most reasonable mechanisms by which large quantities of salt are transferred into the upper parts of playa sediments.

(4) Salt-encrusted puffy areas were more numerous around Test Hole 2 than in any other area of the playa, which offers additional evidence of ground-water discharge through the playa surface (Figs. 8 and 9). The numerous patches of puffy salt-stained ground extended in all directions around the test hole. The longest dimensions of patches ranged from a few inches to more than 3 or 4 feet. Similar to other areas of Coyote Playa, some patches appeared to be controlled by fractures and cracks on the playa surface. Following the completion of Test Hole 2, water rose in the hole and flowed onto the surface. Two potentiometric observation pipes were cemented into the hole, one at a depth of more than 200 feet and the other at a depth of 40 feet. Although the deeper pipe was cemented, water slowly leaked around the edge of the cement block. Therefore, the salt-encrusted puffy ground was probably formed by water moving upward around the cement plug from the deeper artesian zone into the shallow 10- to 25-foot zone of subsurface permeability, and thence by capillarity to the surface.

(5) Linear zones of salt-encrusted ground along the margins of an east-west road crossing the southern part of Coyote Playa may have been formed from rapid and concentrated capillarity (Fig. 10). Capillary discharge probably was retarded in the compacted clays beneath the road, thereby diverting the water to the less compacted clays of the road margins. At Troy and Harper Playas, which are characterized by rapid capillary discharge, the zones of puffy ground were from 1/2 to 1 foot high in places along the roads (Chap. 7, Fig. 6).

Conclusions

At Coyote Playa ground water occurs (1) in a shallow zone of subsurface permeability from 10 to 25 feet deep, and (2) under artesian head in a deeper zone of gravel and sands which underlie or interfinger with the playa clays. Discharge from the 10- to 25-foot zone is probably by capillarity accompanied with evaporation at the surface; whereas, discharge from the deeper aquifer is probably from artesian rise of ground water accompanied by capillarity. Some ground water throughout parts of the playa may discharge by escape of water vapor if there is an increase in vapor pressure with depth and a decrease in temperature with depth (Gordon Stewart, Soil Physicist, University of Massachusetts, oral communication).

Recharge of the 10- to 25-foot zone of subsurface permeability occurs primarily during times of playa flooding. The hydrogeologic effects of each flood are immediate because the flood water flows rapidly through giant polygonal fissures. Consequently, the influence and characteristics of the shallow ground water are probably related to short-term climatic fluctuations. Water in the deeper artesian zone is recharged through large alluvial fans and ephemeral streams draining into Coyote Valley; therefore, under natural conditions potentiometric fluctuations and hydrogeologic effects of water in the deeper zone are probably related to long-term changes of climate (see also Neal and Motts, 1967, p. 514).

In shallow playa sediments the amount of the moisture from infiltration of the surface water probably influences the amount of ground-water discharge from the deeper aquifer. During years in which abundant moisture is present in the 10- to 25-foot zone of subsurface permeability, relatively smaller amounts of discharge may occur from the deeper artesian aquifer

Figure 9. Small area of salt-encrusted puffy ground near Test Hole 2.

Figure 10. Salt-encrusted ground along road in south-central part of playa is evidence of capillary discharge through playa surface. Note isolated areas of salt-encrusted ground throughout other parts of playa surface.

because of the tendency to reverse the shallow to deep moisture gradient. It may be that large amounts of deeper ground water can discharge only in more arid years when a low moisture content is present in the surficial clays.

Discussion on Origin of Surface Types

If ground water is discharging through the surface of Coyote Playa by processes of capillarity and hydrostatic drive as described in previous sections, then these processes may also explain the formation of some areas of puffy ground and areas of wavy undulating ground on Coyote Playa. Hagar (1966, p. 51) concludes that some areas of puffy ground are not related to ground-water discharge, including a large area of stable puffy surface north and east from Coyote Wash and areas in the northern parts of the playa which change alternately from a puffy to a hard condition. He concludes that the distribution of the above-mentioned stable and unstable puffy areas is related to their proximity to major ephemeral streams entering the playa, and that relatively frequent but intermittant floods promote the development of puffy ground by water infiltration a few inches deep, followed by lateral movement and capillarity. He concludes that areas of the central playa retain their hard, compact nature from less frequent flooding and less contact of the playa clays with water.

On the other hand, I suggest an alternative hypothesis that the above-mentioned areas of puffy ground are associated with discharge of ground water through the playa surface. The central part of Coyote Playa has a relatively smooth, compact crust because this part of the playa has low capillary discharge and slow formation of puffy ground; flooding keeps the playa crusts in a permanent, compact, hard state. The proximity of the above-mentioned puffy ground areas to the western, northern and southern

playa margins may be caused by more rapid ground-water discharge from tongues of sand and gravel that interfinger into the playa clays near the playa margins. The beds of sand and gravel may extend thousands of feet into playa clays, producing an irregular subsurface interface similar to that in other fine-grained playas such as North Panamint and Rosamond. Artesian ground water can readily move upward through relatively thin surficial clays in the marginal areas; whereas, upward movement is very slow through the thicker clays near the playa center.

The large area north of Coyote Wash (Fig. 1) has constant conditions of puffy ground because this area may be topographically higher than the surrounding playa surface, thus not subject to frequent floodings. Reconnaissance field studies indicated that parts of the surface were 4 to 6 feet higher than Coyote Wash. If future studies are made in Coyote Playa, it is recommended that a microrelief map be made of the playa surface in order to verify the above hypothesis.

It is hoped that the ground-water hypothesis of puffy-ground formation on Coyote Playa will stimulate discussion and promote further work on the origin and development of playa-surface types.

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CHAPTER 4: RECONNAISSANCE GEOLOGY OF BIG SMOKY PLAYA, NEVADA

Robert F. Walker[1]

Ward S. Motts

ABSTRACT

Big Smoky Playa, in the southern part of Big Smoky Valley, Nevada, is surrounded on the north, southeast, and southwest by mountain ranges and on the northeast by a low alluvial divide. Well-developed shoreline features encircle the playa with remarkable symmetry, suggesting that the location of a Pleistocene lake (Lake Tonopah) influenced the size and shape of the playa. Surface types on Big Smoky Playa in 1965 ranged from a hard, smooth surface to a soft, puffy one, with a transition surface having some characteristics of the former two. The hard, smooth surface occupied 23 percent of the playa area, and was underlain by relatively dry sediments to depths ranging from 5 to 15 feet. The salt-encrusted, puffy surface occupied 30 percent of the playa area, and was underlain by a shallow water table at depths from 3 to 5 feet. The transition surface occupying 47 percent of the playa area had a dry crust underlain by moister and darker sediments. Several holes were augered beneath the transition surface, in one place to a depth of 20 feet; however, a water-bearing zone was not penetrated. From field studies and from laboratory determinations, no significant textural difference was found in the sediments underlying the puffy areas and the smooth hard areas. It was concluded that ground-water discharge from a shallow aquifer controls the formation of puffy ground on Big Smoky Playa. The shallow aquifer consists of complex interfingering of permeable lenses of sand and coarse silt within the less permeable silt and clay. Water under hydrostatic head fills the sand-silt lenses and capillary from these lenses produces the puffy ground. Giant desiccation polygons, measuring about 50 yards on a side, were present in two separate areas of the playa; each covered about 350 acres. Phreatophyte Mounds, capped by pickleweed, were 15 to 20 feet wide in their longest dimension and 5 to 12 feet high. The location of high mounds near the margin of the playa was controlled in part by artesian conditions in shallow-playa aquifers.

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[1]Geologist, Chevron Oil Company, Jackson, Mississippi.

INTRODUCTION

Big Smoky Valley is in west-central Nevada about 15 miles northwest of Tonopah. The valley is elongate in a north-south direction and has an interior drainage area of about 3,375 square miles. Three topographically closed basins occupy Big Smoky Valley, two of which contain playas. This study is concerned with Big Smoky Playa and adjoining areas in the south portion of the valley bounded by lat. 38° 30' N and lat. 37° 50' N, and by long. 117° 00' W and long. 117° 50' W (Fig. 1). Big Smoky Playa covers an area of 16 square miles in a shape similar to a distorted figure eight; the northern area is somewhat circular with a radius of about one mile, and the southern ellipsoidal area is about 7 miles long and 2 miles wide. Between these two areas, the surface narrows to one-quarter mile in width. Well-developed shoreline features encircle the playa with remarkable symmetry, suggesting that the location of a Pleistocene lake (Lake Tonopah) influenced the size and the shape of the playa.

Big Smoky Valley received little attention from geologists before rich ore deposits were discovered in the vicinity of Tonopah in 1900. Shortly after ore was discovered, the region was visited by numerous geologists. Turner (1900) described the Esmeralda Formation of Tertiary age which crops out in the ranges bordering the valley on the south, and Spurr (1905) made an extensive study of the Tonopah district. Later Meinzer (1917) made a ground-water study of the entire valley and mapped the Quaternary deposits. Ferguson, Muller, and Cathcart (1953) mapped the geology of the Coaldale Quadrangle which includes a portion of the area studied in this report. Geologic mapping on a regional scale is incomplete at the time of this writing; however, recently Albers and Stewart (1965) have prepared a

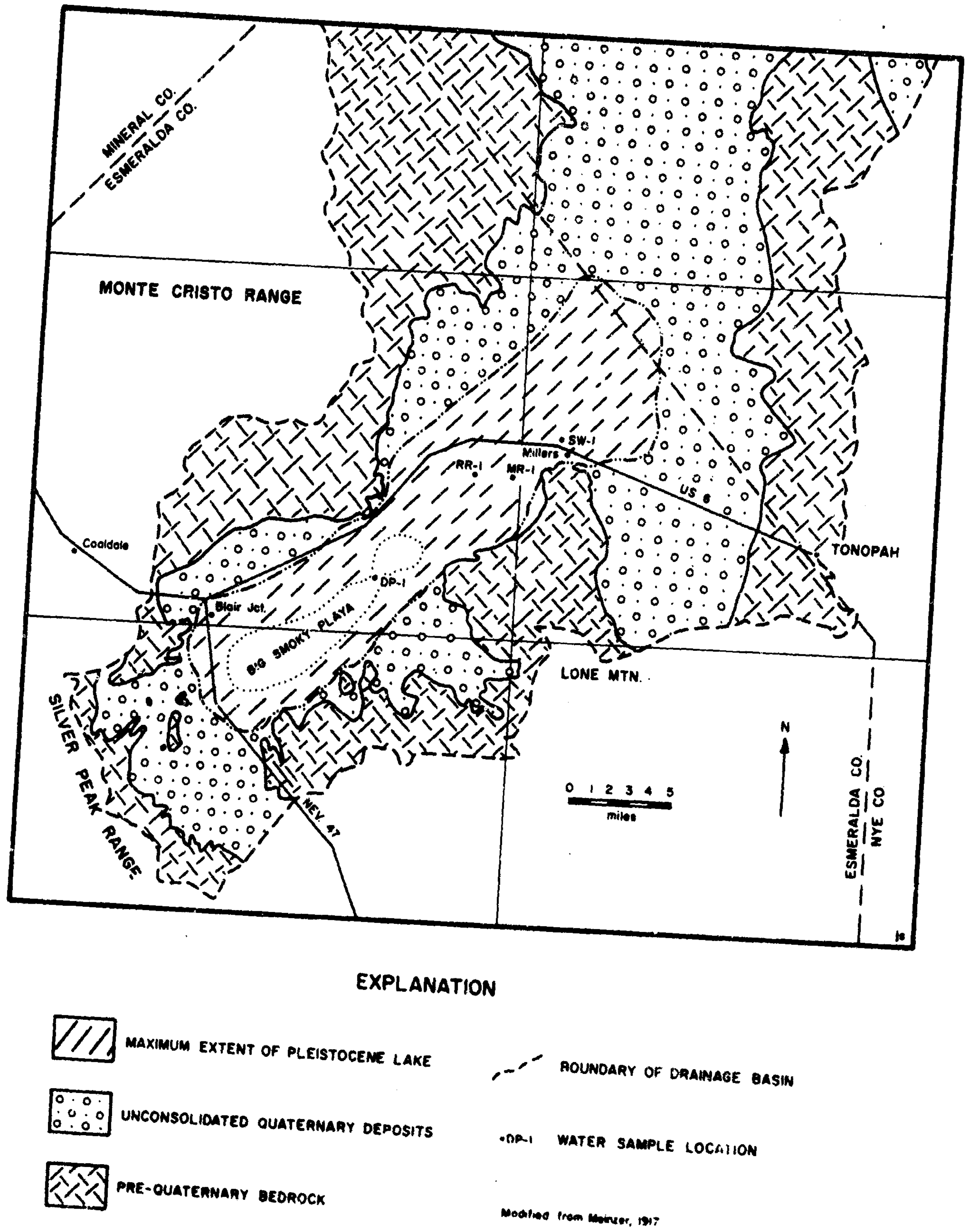


Figure 1. Geological location map of Big Smoky Playa.

preliminary geologic map of Esmeralda County. A general ground-water study including the area of Big Smoky Playa was made by Robinson (1953); Rush (1968, p. 26, 27) calculated the subsurface outflow from Big Smoky Valley into Clayton Valley. This report is based on a Master's thesis by Walker (1966) who engaged in field work during the summer of 1965, and on the observations of Motts who studied the playa for periods of one to two days on five occasions from the summer of 1963 to the winter of 1967-68.

Climate

The amount of precipitation in the area of Nevada around Tonopah is related principally to the topographic elevation. Rush (1968, p. 18) indicates that in general the valley floors and playa surfaces receive an average of about 3 to 5 inches of precipitation per year; the alluvial aprons ranging in altitute from about 4,500 to 5,500 feet receive an average of about 4 to 6 inches; and the highest mountain areas may have an average annual precipitation of 15 inches or more. Walker (1966, p. 22) calculated the average annual precipitation from 1906 to 1965 as 4.67 inches from a composite record based on recordings from the town of Tonopah (elevation 6,090 feet), the Tonopah airport (elevation 5,426 feet), and Coaldale (elevation 4,634 feet). From 1941-64 the average annual precipitation at Coaldale was 3.31 inches. The elevation of Coaldale most nearly approximates the elevation of Big Smoky Playa. Robinson (1953, p. 139) reports a 19-year dry period from 1918 through 1936 intervening between two wet periods, 1906 through 1917 and 1937 through 1949. Walker (1966, p. 22-24) suggests that this latter wet period ended in 1950, a dry period followed until 1962, and another wet cycle began in 1966. The mean monthly precipitation is variable and distri-

buted unevenly through the year. During 1965, for example, almost twice as much precipitation fell in November (1.71 inches) as in any other month.

During the summer of 1965 precipitation throughout the east-central part of Nevada was considerably higher than normal. At Tonopah, U. S. Weather Bureau records indicate the precipitation in 1965 averaged one inch above the 59-year mean calculated by Walker. Local residents claimed that the summer was one of the wettest that they could remember in the last decade. Average rainfall during June, July, and August amounted to .31 inches.

Big Smoky Valley has wide variations of temperature both daily and seasonally. The mean annual temperature at Tonopah is approximately 50° F. (Robinson, 1953, p. 140). Highest temperatures on the playa occur during the summer months, and occasionally reach 100° F. The highest temperature at Tonopah during 1965 was 95° F. (July 5) and the lowest, 3° F. (January 1).

Records of relative humidity are not kept by the present recording stations, but datum from 1930 gives an average value of relative humidity for Toncpah as 45 percent. During the summer months the humidity may drop as low as 5 percent in the late afternoon. At Tohopah the annual evaporation rate from shallow lakes is approximately 65 inches (Visher, 1954, p. 191).

GEOLOGIC AND GEOMORPHIC FRAMEWORK

Big Smoky Playa is surrounded on the north, southeast, and southwest by mountain ranges and on the northeast by a low alluvial divide. The playa is flanked on the north by the Monte Cristo Range, on the southwest by the Silver Peak Range, and on the southeast by Lone Mountain and adjacent hills (Fig. 1). Lone Mountain (elevation 9,103) is the highest point in the drainage basin and is located 15 miles west of Tonopah. The Silver Peak Range forms the drainage divide for Fish Lake Valley on the southeast and for Columbus Marsh on the west.

The bedrock hills surrounding the playa are formed predominantly of plutonic and volcanic rocks with minor amounts of sedimentary rocks. The main mass of Lone Mountain consists of intrusive granite; its southern extension is a low, south-trending ridge of volcanic rocks. The western face of the mountain is a bold fault-line scarp rising over four thousand feet above the valley floor in a horizontal distance of about one mile. The Silver Peak Range primarily consists of volcanic and sedimentary rocks of Tertiary age. The volcanics include basalt, rhyolite, tuff, and welded-ash flows and the sedimentary rocks include conglomerate, limestone, siltstone and shale. The Esmeralda Formation crops out in the shallow washes near the playa and can be traced up-slope to the mountains, where it forms a large part of the Silver Peak Range. The Monte Cristo Range is a crescent-shaped mountain mass which joins the Cedar Mountains on the east and the Pilot Mountains on the west; the range is underlain predominantly by phyllites, andesites, and rhyolite breccias, "welded" rhyolitic ash flows and basalt of Quaternary age. The Monte Cristo Range is exceptionally colorful when viewed from a distance because of the multicolored aspect of the andesites and rhyolites.

Flanking the mountain ranges and sloping gently toward the central portion of the basin are broad desert plains consisting of alluvial fans, bajadas, and pediments. Alluvial fans along the scarp of the western side of Long Mountain are less than one mile across in their distal portion where they merge into the flat valley floor. A prominent lake terrace formed during one of the stages of ancient Pleistocene Lake Tonopah cuts into the steep fans, indicating that the fans probably formed before the lake stage as the result of faulting that took place along the western face of Lone Mountain. The material in the fans consists mostly of large granitic blocks that show well-developed exfoliation and were possibly rafted by ancient mud flows. Desert varnish in the fans is not prominent because of the large proportion of gravels consisting of granite and similar acidic rocks.

A broad slope flanking the Silver Peak Range at the southern terminus of the valley is a pediment surface approximately four miles wide and almost entirely covered with alluvium except for a few bedrock exposures. The profile of this surface is concave upward, with a gradient of 500 feet per mile near the mountains, decreasing to 50 feet per mile in the distal portion near the playa. This pediment surface is cut on the relatively soft shales and sandstones of the Esmeralda Formation and continues in a broad arcuate pattern toward the northeast and the northwest, so that the entire southern portion of the valley is encircled by the erosional surface. Pediments also form the topographic divides that separate Big Smoky Valley from Clayton Valley and Columbus Marsh; therefore, the divides are probably pediment passes (Howard, 1942, p. 3).

The extensive, relatively flat, "desert flat" extends between the broad piedmont slopes and the playa. Whereas the gradient of the alluvial slopes

ranges from several hundred feet per mile to about 50 feet per mile, most of the desert flat possesses a gradient that ranges from about 15 feet per mile to about 6 feet per mile. The materials underlying much of the desert flat can probably be classified as bajada because of their thickness. Northwest of Millers a well in the desert flat is reported to have been drilled through 670 feet of alluvial materials before penetrating bedrock (Meinzer, 1917, p. 109). In Big Smoky Valley, the desert flat is nearly 40 miles long and from two to seven miles in width. The vegetation and surface appearance of the desert flat is similar to the higher pediment slopes, with the exception of small playa-like areas where drainage collects due to natural or man-made obstructions such as dunes or roads. These small areas or microplayas, generally a few hundred feet in size, are characterized by fine-grained sediments, and exhibit a hard, dry, mud-cracked surface.

GEOMORPHOLOGY OF BIG SMOKY PLAYA AND ADJACENT AREAS

The lowest elevation of Big Smoky Playa (4,720 feet) is located in the northeastern quarter of the southern part of the playa. About 4 miles east of this area the playa elevation rises to 4,723 feet. The angle formed by the surface and a horizontal plane between these two locations is approximately 30 seconds, a gradient of 0.75 feet per mile.

In most places the playa does not directly border the desert flat but is surrounded by a narrow area herein called a "playa-transition zone" that ranges from a few to several hundred yards in width. The vegetation and sedimentation of this zone are a transition between the desert flat and the playa; vegetation occurs in the zone, but the playa is barren. Sediments of the playa-transition zone are lacustrine silts and clays veneered with a cover of granules and pebbles probably derived from the adjoining desert flat. Large phreatophyte mounds and extensive areas of wind-blown sand occur in the playa-transition zone.

The playa is positioned asymmetrically in the drainage basin, one mile from Lone Mountain on the east and 3 to 10 miles from the Monte Cristo Range on the west. The asymmetric position of the playa can be explained by differential tilting of the basin. Eastward tilting is suggested by the presence of small, steep alluvial fans that terminate abruptly at the base of Lone Mountain. The small fans contrast with the broad, well-defined slopes which border the valley on the western side, a relationship that suggests relatively more tectonic movement along the eastern border of the valley. The position of the playa can also be explained as the result of more rapid deposition from the west which has "pushed" the playa eastward by the encroachment of detrius.

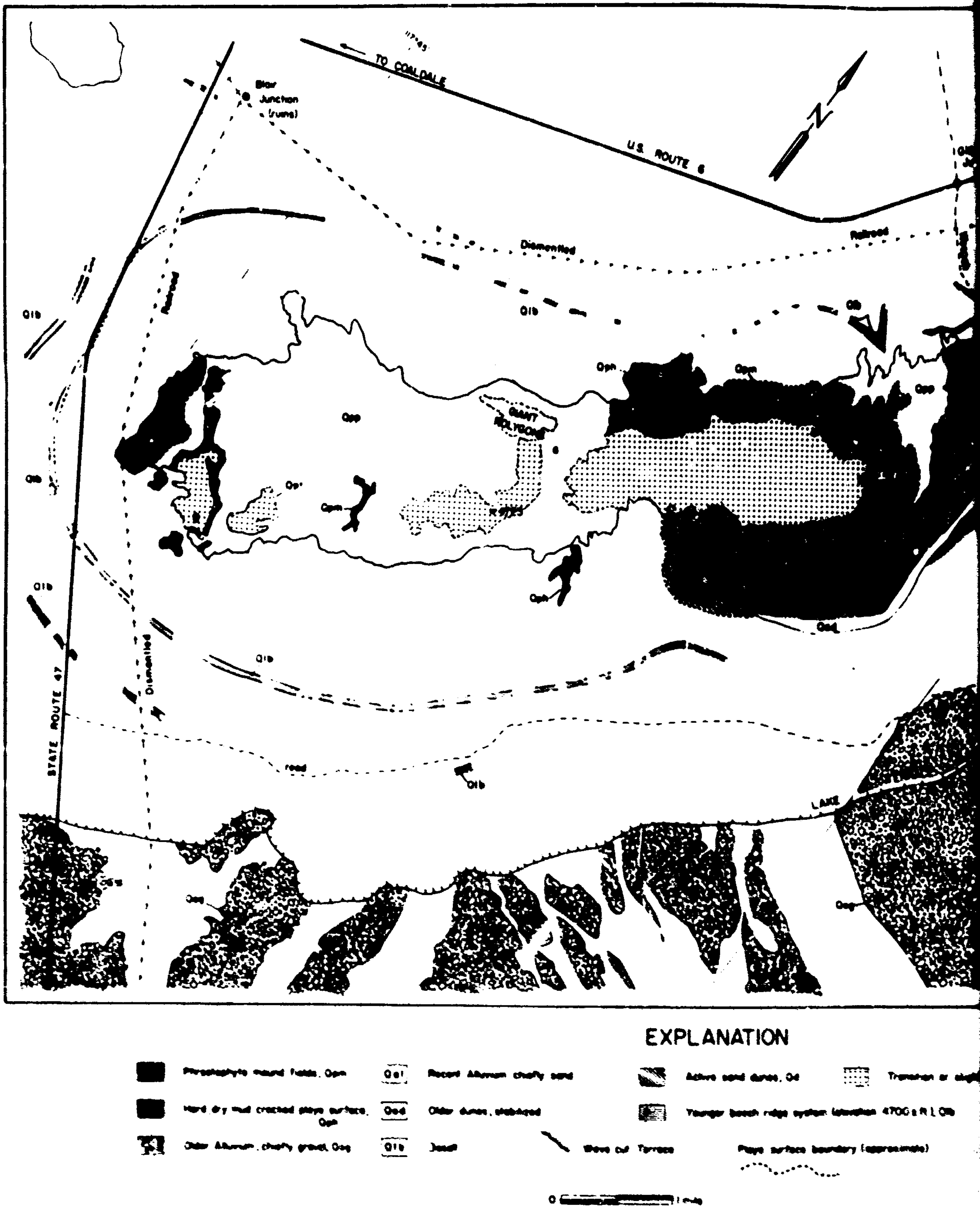
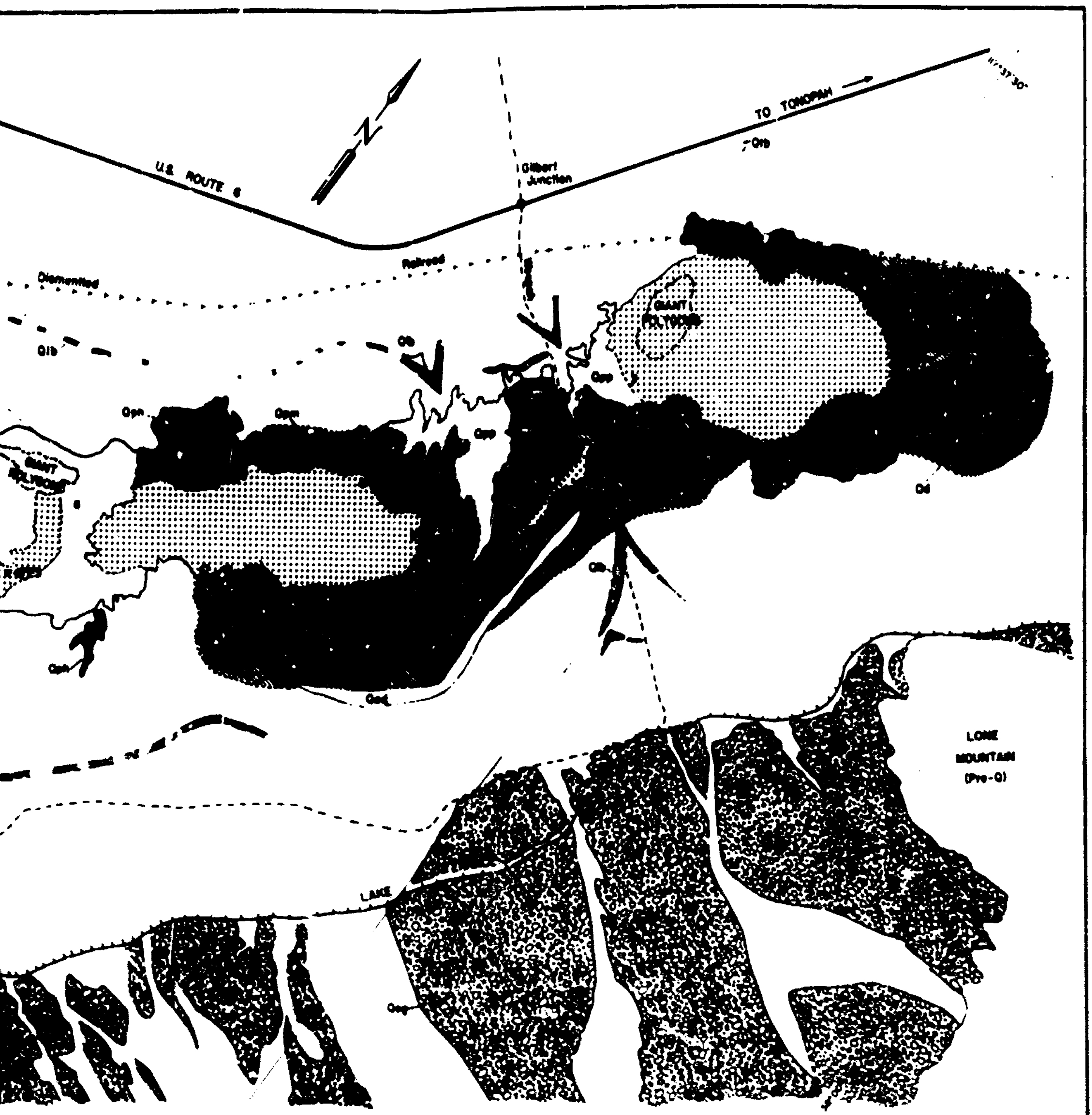


Figure 2. Geologic map of Big Smoky Playa and adjacent areas.

A



EXPLANATION

...um shaly sand | Active sand dunes, Qd | Transition or slightly puffy playa surface, Qpt | Qpp Puffy playa surface

..., stabilized | Younger beach ridge system (elevation 4700 ± ft), Qlb | Older beach ridge system (elevation 4800 ± ft), Qlb

Wave cut Terrace | Playa surface boundary (approximate) | Mapped by R F Walker, 1965

0 — 1 mile

d adjacent areas.

β

Playa Surface Types

Surface types of Big Smoky in 1965 ranged from a hard, smooth surface to a soft, puffy surface (Fig. 2). These two surface types are end members with a third or transition surface having characteristics of the two. The boundary between surface types was generally gradational and the contacts shown on Figure 2 were approximate.

Hard Surface

In 1965 the typical hard surface was very pale yellow, smooth and dry with almost no microrelief, and covered about 3.5 square miles or 23 percent of the playa area. The surface was characterized by several generations of small desiccation polygons generally less than six inches across. Areas of the hard surface occurred principally in the northern part of the playa, and in limited areas of the desert flat where drainage was locally ponded. Automobiles could easily cross the hard, compact surface at moderate to high speeds and leave no tire impressions (Fig. 3).

Approximately 15 holes were augered at locations throughout the dry surface to depths ranging from 5 to 15 feet. No variation in the moisture content of the subsurface sediments was noted from field inspection. The fine-grained sediments were very dry, and they commonly slipped through the auger head before it could be withdrawn to the surface. The dry nature of the materials at depth indicated that little ground water discharged through the dry surface by capillarity. The surface had no alkali stain, but the sediments reacted vigorously with dilute hydrochloric acid, indicating the presence of carbonates.

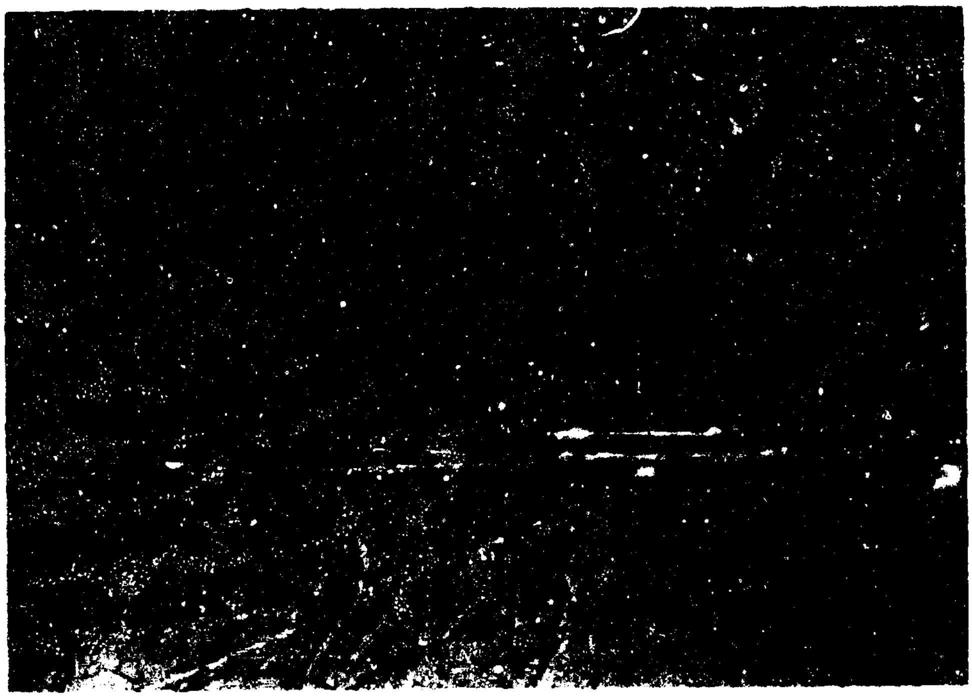


Figure 3. Hard, dry, and smooth surface (QPH).

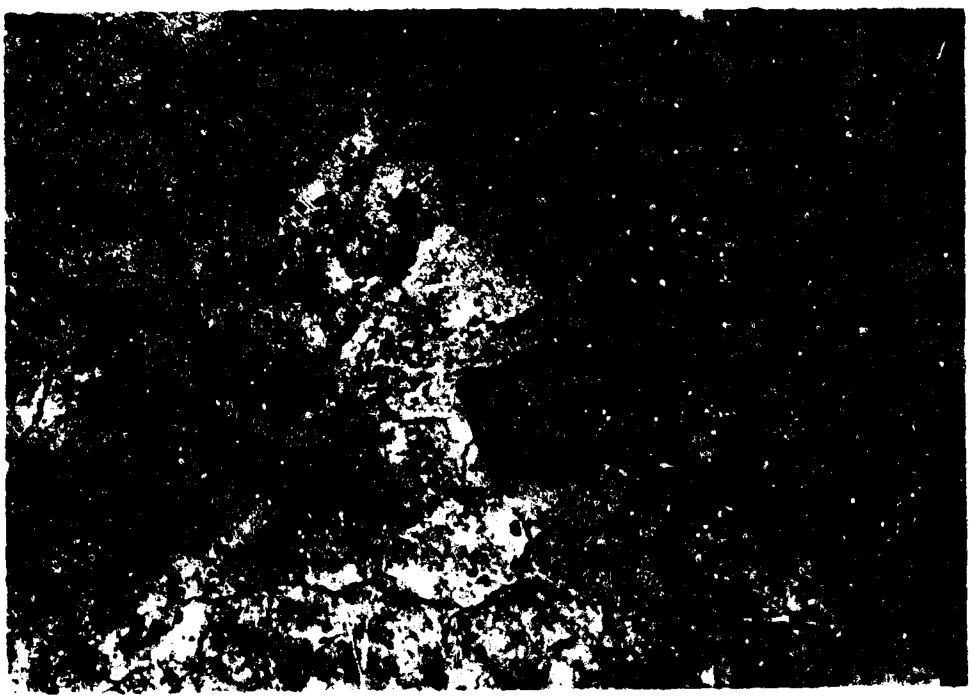


Figure 4. Puffy surface (QPP) on which are irregular white salt-encrusted areas.

Puffy Surface

A dark, yellowish-brown, puffy surface covered 5 square miles or 30 percent of the playa area in 1965 (Fig. 4). White patches of salt were present throughout the surface whose microrelief ranged up to 6 inches. The crust was dry, but sediments beneath the puffy surface were moist and slightly darker in color. Automobile tires sank from 2 to 4 inches into the crust, and it subsided under the weight of a man.

Approximately 10 holes were augered into the puffy surface at selected places around the playa, and a 3 by 4 foot trench was dug in the narrow southern part of the playa (DP-1, Fig. 2). In all places the water table was penetrated at depths ranging from 3 to 5 feet and the sediments were moist from the surface to the water table. The trench (DP-1) encountered very slow artesian flow at a depth of 40 inches. Ground-water discharge from these near-surface aquifers appears to control the formation of the puffy ground.

Transition Surface

The transition surface was so named because its appearance and characteristics were intermediate between the hard, dry surface and the soft, puffy surface. Automobile tires sank slightly into the surface, but man's walking left no footprints (Fig. 5). The transition surface was the most widespread surface type and covered 7.5 square miles or 47 percent of the playa area. The surface had a yellowish-gray color and microrelief ranged from 1 to 3 inches. The crust was dry, but just beneath the surface sediments were slightly moist and darker in color. Several holes were augered beneath the surface, at one place to a depth of 20 feet; however, a water-bearing zone was not penetrated.

Figure 5. Transition surface, note tire imprints about 1 inch deep made by car.

Figure 6. Typical phreatophyte mound in eastern part of Big Smoky Playa.

Pebble Cover

Scattered over parts of the surface of Big Smoky Playa was a sparse cover of granule and pebble-size fragments which generally ranged in diameter from one-half to one inch. The pebbles were angular to subangular, of mafic composition, and similar in size and composition with those in the desert flat, indicating they were probably derived from this latter area. No gravels were found in the subsurface. The density of this pebble cover was greatest at the playa margins and decreased toward the playa center where in places there was a maximum density of three or four pebbles per square foot.

Giant Desiccation Polygons

Giant desiccation polygons, occurring in numerous playas, are formed from deep contraction caused by desiccation of the fine-grained sediments (Neal and Motts, 1967, p. 515-518). On Big Smoky Playa there were no recently-formed giant desiccation polygons, but there were relic fissures filled with coarse sand and silt that supported xerophytic vegetation. These ancient polygons measured about 50 yards on a side and were present in two separate areas--one in the northern and the other in the southern part of the playa (Fig. 2). Each of these areas covered about 350 acres. Both of the polygon areas were near the edge of the playa, and were slightly higher than the main part of the playa. Relic fissures did not occur on or near the lower, central part of the playa. On aerial photographs, the polygons could be recognized easily by their regular, geometric pattern, which was delineated by vegetation.

Phreatophyte Mounds

Plant mounds are small hills, generally a few feet high, of wind-deposited material capped by one or more living or dead desert plants (Fig. 6). Phreatophyte Mounds at Big Smoky Playa differ from those at other playas by their height (5 to 12 feet), by their thick crust (as much as one inch) cemented with calcium carbonate, and by their association with phreatophytes (Motts, 1965, p. 19).

Meinzer (1917, p. 49) first noted the occurrence of large plant mounds at Big Smoky Playa and described their development as follows:

> A mound may have its origin in a single alkali-resistant bush which is able to establish itself on the flat. This bush, by acting as a windbreak, and accumulating a little wind-borne material, produces conditions that are favorable for plant growth in its immediate vicinity. It does this by providing a less dense, less alkaline, and better drained soil than that of the flat, and by providing some immunity from inundation.

Phreatophyte Mounds are roughly circular to elliptical in shape, and sometimes resemble miniature drumlins in plain view. The larger mounds are commonly 15 to 20 feet in longest dimension along their base. Heights of mounds range from 5 to more than 12 feet along the margins of the playa. The mounds commonly are capped by big greasewood (<u>Sarcobatus vermiculatus</u>), which generally have very deep root systems--depths of 20 to 40 feet are not uncommon (Meinzer, 1927, p. 41).

A cross section through a typical mound shows well-developed eolian cross bedding. Texturally, Phreatophyte Mounds contain more sand than the playa sediments, and more silt than clay dunes. Because the mounds consist of thinly interbedded units, it is impossible to sample a single sedimentation unit without contamination from adjoining units. A channel sample of

a typical Phreatophyte Mound from Big Smoky has the following textural characteristics: sand 53%, silt 16%, clay 31%.

The hard carbonate crust of Phreatophyte Mounds is formed by capillary and plant water discharging through the mound sediments. This discharge is necessary to maintain the cemented crust, and the height to which the crust can be maintained appears to be related to the potentiometric level of artesian aquifers. Trenching shows that shallow artesian conditions are present in the vicinity of the large mounds at Big Smoky Playa, suggesting that large mounds at other playas may be dependent on similar conditions. When the plant dies and the crust is removed by erosion, the fine-grained materials inside the mound desiccate and are easily removed by rainwater or wind, thereby leading to the total destruction of the mound.

Phreatophyte Mounds tend to occur in groups rather than as single isolated hills. Long, linear groups of mounds joined in places by recent wind-blown sand occur along the western border of the playa (Fig. 2). The longer groups tend to have a sub-parallel alignment with beach ridges that lie up-slope from the playa.

Deflation of Playa Sediments

Wind erosion has apparently been an effective process in removing playa sediments on Big Smoky Playa. When Motts first visited the playa in July, 1962, the central part of the playa surface was covered with mud curls or concave-upward polygons formed from recent flood deposits (Chap. 7, Fig. 26). Two years later when Walker studied the playa all evidence of the mud curls was gone; they had been removed by wind deflation. The actual process of the removal of the mud curls was observed by the authors before and during a heavy thunderstorm in August, 1965. Most of the wind erosion occurred before the storm, during a time of strong upward winds. The wind carried large quantities of the mud curls hundreds of feet into the air (Fig. 7). At the same time abrasion of the curls occurred as the wind carried them by traction along the ground surface.

Two additional lines of evidence indicate that the playa sediments have been removed by wind erosion. First, numerous channels are incised below the desert flat surface surrounding the playa (Fig. 8). These channels have been cut into a surface that formerly was level with and in sedimentary equilibrium with the old playa level. When the playa surface was lowered by erosion, the stream achieved a new base level by incising through the desert-flat surface. Secondly, large areas of the transition playa surface and the adjacent desert flat contain small sand mounds, some of which are capped by xerophytes and some of which contain dead roots (see Fig. 9). These mounds have a common level, and the plants that formed the mounds may have grown on the older, higher surface.

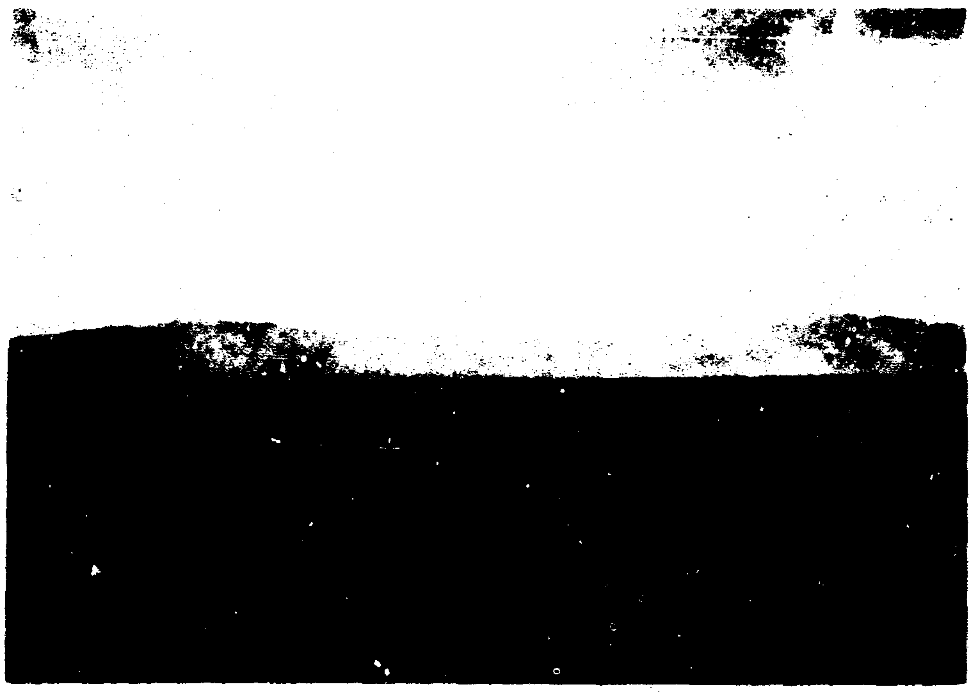


Figure 7. Wind erosion carrying playa sediments high in the air by strong upward winds.

Figure 8. Channel, near playa margin, that has cut into desert flat.

SEDIMENTATION AND HYDROLOGY

Sedimentation

Representative playa samples including the three playa-surface types and playa-sedimentation units were collected and analyzed for textural composition (Table 1 and Figs. 9, 10, 11). Material coarser than 4 Ø (sand fraction) was removed from the samples by wet sieving, and the mud fraction was analyzed using the pipette method described by Folk (1964, p. 36-39). The relative percentages of sand, silt, and clay were calculated for each sample and plotted on a triangular textural diagram (Fig. 10). All playa-surface samples are in the sandy mud and sandy clay range and no significant textural differences in the sediments occur at shallow depths (1 to 4 feet). The sand fraction of each of the samples was examined under the binocular microscope to obtain a visual estimate of the mineral composition. Common constituents are volcanic rock fragments (30-40%), quartz (30-40%), gypsum (10-20%); accessory minerals are mica, carbonates (dolomite and/or calcite), and heavy minerals (mostly amphibole and pyroxene).

Extensive flooding of the playa during August, 1965, (Fig. 12) gave Walker an opportunity to study the relation of flooding to playa sedimentation processes. Following flooding early in the day, a sheet of water was relatively still and undisturbed. However, by late afternoon the wind shifted the sheet and placed much of the finer material in suspension, as shown by the turbid appearance of the water. The flooding also provided additional evidence of the low permeability of the playa surface and of the small quantities of water infiltrating the subsurface. When the lake had receded, the top few inches of the hard (Qph) crust were turned over with a shovel revealing completely dry, shallow sediments.

TABLE 1

LOCATION AND DESCRIPTION OF PLAYA SAMPLES

Sample	Location*	Map Symbol	Description
1	surface crust	Qph	hard surface
2	surface crust	Qph	hard surface
3	surface crust	Qpt	transition surface
4	surface crust	Qpt	transition surface
5	surface crust	Qpp	puffy surface
6	surface crust	Qpp	puffy surface
7	4 ft. beneath surface	Qph	area
8	3 ft. beneath surface	Qpt	area
9	3 ft. beneath surface	Qpp	area

*Locations of samples are shown on Figure 2 and size analyses are shown on Figure 12.

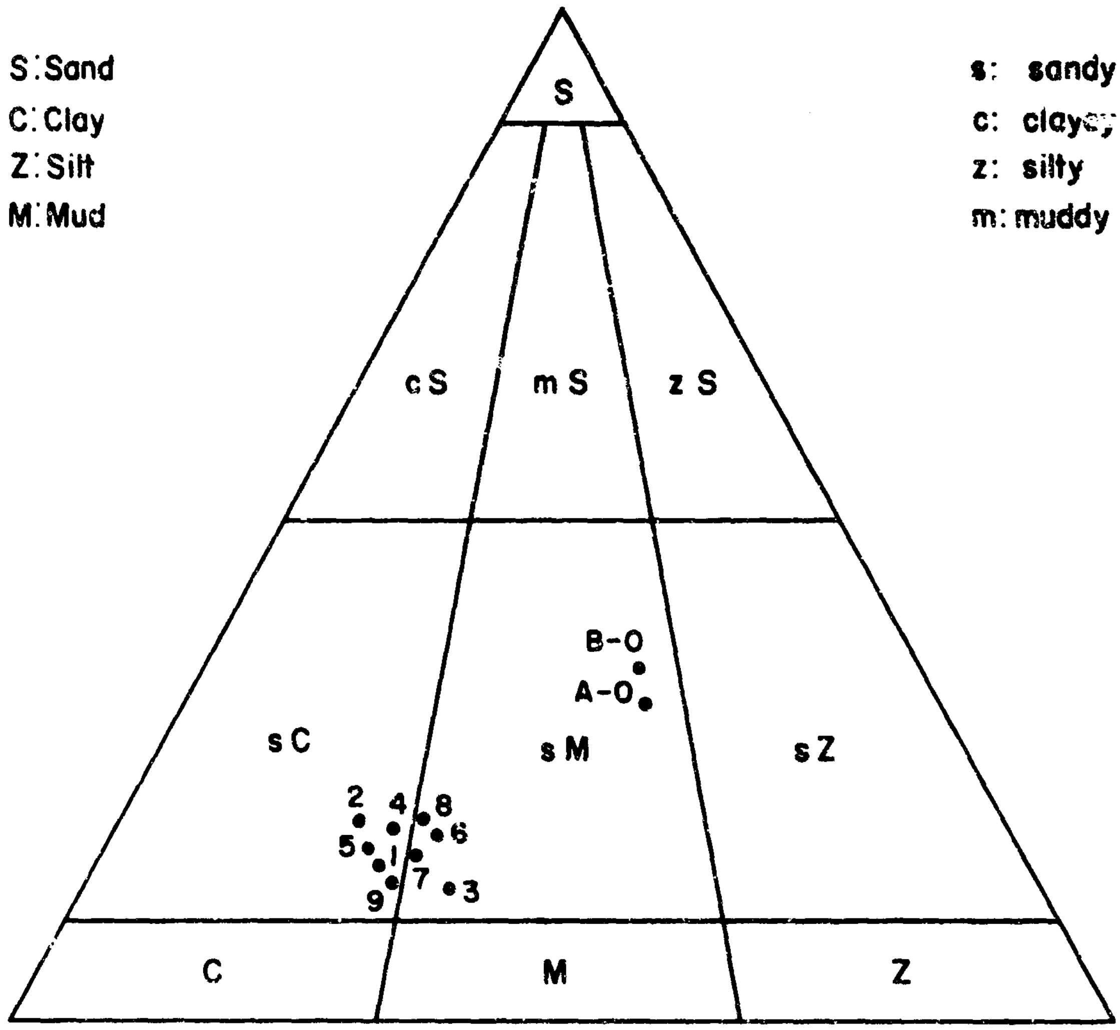


Figure 10. Triangular plot of playa sediments. For location of samples see Figure 2, and for description see Table 1.

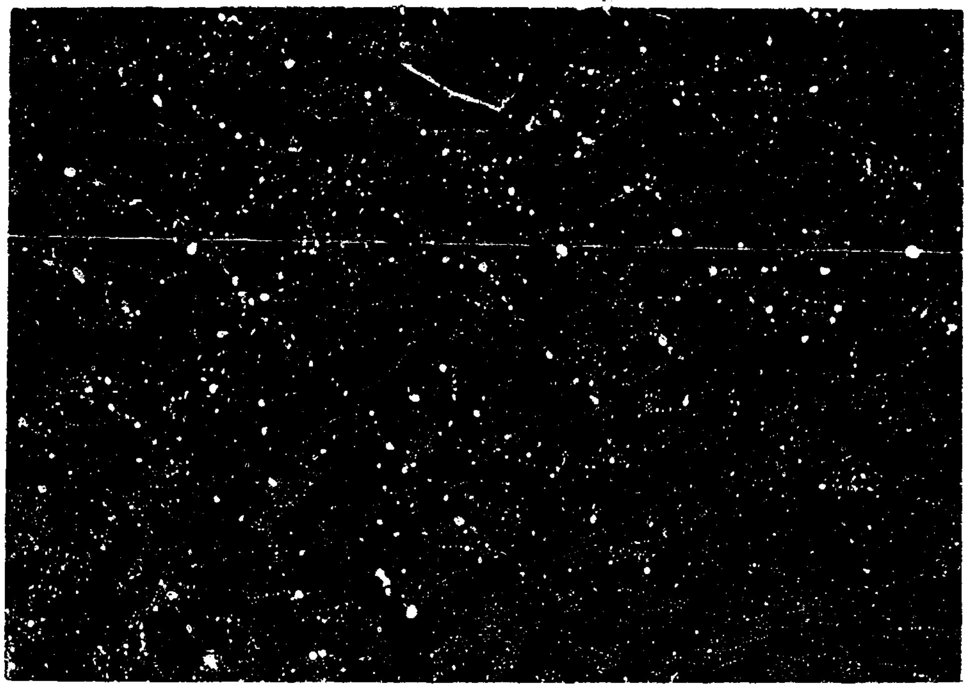


Figure 9. Small mounds in eastern part of playa.

Figure 11. Playa sedimentation unit (mud curl) consisting of basal sand and silt grading upward into finer sized silt and clay. Note curls beginning to form in left part of photograph as sedimentation unit desiccates.

Recession of water from Big Smoky Playa between successive floodings gave Walker an opportunity to study the sediments deposited during these floodings. The term "playa-sedimentation unit" was used to designate the sediments deposited after one ephemeral flood. Each unit was a graded bed consisting of basal sand and silt grading upward into finer-sized silt and clay. The average unit was about 0.05 to 0.10 inches thick. Toward the center of the playa where the sandy basal portion was not deposited, only a very thin unit of silt and clay was laid down. Two samples (A-O and B-O, Fig. 10) of the graded beds from the playa edge were analyzed texturally, and showed a much greater sand content than samples from the fine-grained playa surface. It was not possible to sample the very thin sedimentation units near the center of the playa without mixing and contaminating them with playa-surface sediments.

Hydrology

Big Smoky is a bypass type of hydrologic valley; i.e., some of the water draining from the surrounding mountains discharges through the playa surface, and part of the water travels downgradient where it is discharged in valleys with lower altitudes such as Clayton Valley and Columbus Flat. Rush (1968, p. 15) reached the same conclusion and estimated the average annual recharge to Big Smoky Valley was 16,000 acre-feet and evapotranspiration from the valley was 4,600 acre-feet. Rush believes that the imbalance of 13,000 acre-feet flows through solution openings in carbonate rocks from Big Smoky Valley into Clayton Valley. Ground-water conditions in Big Smoky Valley have been studied by Meinzer (1917) and Robinson (1953). Meinzer's work is based on considerable well data and personal observations in the area during several years in the early 1900's. Most of the wells cited by Meinzer have since been abandoned and are now filled with debris, making it impossible to obtain recent hydrologic data from these wells.

Meinzer (1917, Pl. 2) found that the potentiometric surface at Millers, located about 12 miles northeast of Big Smoky Playa, was about 100 feet below the surface, whereas near the playa the depth to the potentiometric surface was as shallow as two feet. Ground water in the valley fill flows downgradient toward the playa where some is discharged directly through the puffy surface and some is discharged by vegetation. Meinzer (1917, p. 115) also found that the total dissolved solids were higher in water near the playa. Walker sampled water from four wells that lie along an approximate line from Millers to the center of the playa. Partial chemical analyses of these samples were made using a portable water-quality kit. The results are shown in Table 2 and are in agreement with Meinzer's original findings.

TABLE 2

PARTIAL CHEMICAL ANALYSIS OF GROUND-WATER SAMPLES

Sample	Total alkalinity (as ppm $CaCO_3$)	Chlorides (ppm)	Total dissolved solids (ppm)
DP-1	190	77.5	1,085
MR-1	150	50.0	450
RR-1	180	55.0	420
SW-1	135	15.0	224

Location of samples:

DP-1: Trench along Weepah Road crossing narrow portion of playa. Depth: 5 ft.

MR-1: Millers Ranch, 7 miles northeast of playa. Depth: 10 ft.

RR-1: Abandoned railroad well, about 6 miles north of playa. Depth: 4 ft.

SW-1: State drinking well along U. S. Highway 95 at Millers, about 12 miles northeast of playa. Depth: approximately 200 ft.

Note: See Figure 1 for locations of samples.

During the summer of 1965 Walker dug a shallow trench 5 feet deep through clays and silts near the north end of the playa at station DP-1 (Fig. 2). When the trench penetrated a shallow lens of sand and silt, water under the artesian head flowed over the playa surface (Fig. 13). Motts visited the trench in the fall of 1967 and the water was still flowing. This long-continued artesian flow from such a shallow aquifer is an unusual condition in playas of western United States. The following are three possible explanations for the artesian flow. First, the lens of sand and silt containing the artesian water may extend into the dune sand and alluvium of the desert flat, thereby giving the lens a hydrologic connection with the higher recharge area. Second, water from depth could be ascending through a vertical zone of high permeability in the playa sediments. Motts observed areas of higher ground-water discharge along zones of relatively high permeability on South Panamint Playa and Troy Playa in California. Third, deep water may move upward under hydrostatic head, fill the shallow lens, and discharge by capillarity at the surface. The sustained discharge of water for more than two years would indicate a deep source for the water because the large amount of water that has discharged does not appear to be commensurate with the relatively small recharge area.

The playa was flooded from the latter part of July until the middle of August, 1965, when field study by Walker was terminated. Although water never completely covered the playa, at one time about 75 percent of the surface was inundated to a depth of 6 to 18 inches (Fig. 12). At this time the flooded area included the entire southern part of the playa. According to local residents, playa flooding generally occurs only once or twice in the average summer, and water evaporates from the playa "in a matter of days."

Figure 12. Big Smoky Playa flooded during August, 1965, looking south to Silver Peak Mountains in the background. White zone near water was probably formed by capillary discharge intensified around boundary of standing water.

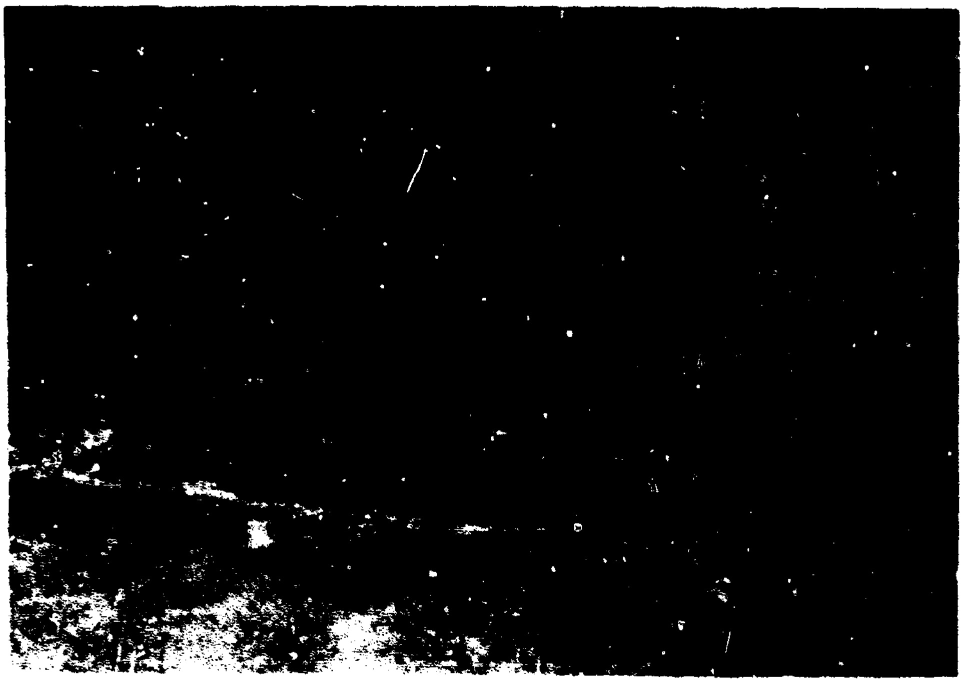


Figure 13. Small pond in 1968 along Weepah Road formed from artesian flowing water. A trench dug by Walker in 1965 penetrated the shallow artesian zone.

Relation of Surface Types to Hydrology

Field evidence at Big Smoky Playa, substantiated by laboratory work, shows a relation between playa-surface types and ground-water depth. As discussed previously, the puffy surfaces are underlain by moist materials, whereas the hard surfaces are not. Laboratory work shows that sediments underlying the different surface types are similar in textural composition; therefore, their relative permeabilities are also similar. In addition, trenching has shown that some of the areas of puffy ground are underlain by sandy lenses. The above evidence suggests that the irregular distribution of puffy, transitional, and smooth-hard surfaces is best explained as complex interfingering of shallow, permeable lenses of sand and coarse silt with less permeable silt and clay. Water under hydrostatic head fills the sandy-silt lenses and capillarity from these lenses produces the puffy-ground conditions. Where sand-silt lenses are not present near the surface or where they occur at great depth, only small amounts of water can escape from the surface, resulting in the hard, smooth surface. The above theory should be substantiated by a more detailed investigation including the drilling of many auger holes in all the surface types.

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CHAPTER 5: GEOLOGY AND HYDROLOGY OF TROY PLAYA

SAN BERNARDINO COUNTY, CALIFORNIA

Charles G. Groat[1]

ABSTRACT

Troy Playa is located in the southeast corner of the Lower Mojave Valley, an area formerly occupied by Lake Manix of late Pleistocene age. A well-preserved beach ridge or bar and brown muds and sands, deposited in Lake Manix, stand a few feet above the eastern margin of the playa.

The upper 10 to 15 feet of playa sediments were delineated into two lithofacies: (1) an upper mud facies grading to sandy mud near the playa margins and (2) an underlying sand facies characterized by sand and muddy sand with granular coarse sand in the upper few inches similar to lag sands of the modern desert flat. The sand facies probably records fluvial and eolian deposition, whereas most of the mud was deposited in ephemeral playa lakes.

Most of Troy Playa has a puffy or self-rising surface produced by capillary discharge of shallow ground water. The shallow water table or top of the saturated zone is 10 to 15 feet below the playa surface; puffy ground is produced where the water table is within the fine-grained mud facies and capillary rise of ground water is pronounced. A hard playa surface is present in the southwestern part of the playa where the water table is within the sand facies. The presence of sand above the water table inhibits capillary rise and permits the development of a hard-compacted playa surface by desiccation. Declining ground-water levels have resulted in a decrease in capillary discharge at Troy Playa which could foster a conversion from a puffy to a hard-compacted playa surface. Compaction by flooding and the desiccation that follows is aiding in this conversion. The dynamic character of the playa surface is also shown by changes in the morphology of the playa surface documented in this report.

Heavy pumpage west of the playa and minimal recharge under present arid conditions have caused a decline in the potentiometric surface throughout the valley. The greater decline in areas of heavy pumpage west of the playa is resulting in intrusion of poor-quality water from the Troy Playa area into fresh-water aquifers west of the playa.

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[1]Geologist, Bureau of Economic Geology, The University of Texas, Austin, Texas.

INTRODUCTION

This chapter on Troy Playa is based on my Master's thesis (Groat, 1967) conducted at the University of Massachusetts. The playa and the adjacent alluvial fans, desert flat, and dune fields are discussed in the thesis; only the geology and hydrology of Troy Playa and the immediate area are discussed in this chapter. The section entitled "Playa Surface, Winter 1967-68" was written by Ward S. Motts.

I worked in the field during the summers of 1963 and 1964 and was assisted in 1963 by my brother, Robert Groat, and in 1964 by William Gordon. Mr. Leroy Tyler, well driller from Newberry, California, provided many well logs and other information.

Geographic and Geologic Setting

Troy Playa is located in the Lower Mojave Valley approximately 27 miles east of Barstow, California (Figs. 3 and 4, Chap. 1). The playa is 9.5 miles long in a north-south direction and 2 miles across in an east-west direction at the widest part in the southern half. The playa tapers toward its northern end where it is only 0.3 mile wide. The Cady Mountains border the playa on the east, the Newberry Mountains border it on the south, and an open basin extends westward for 15 miles from the western playa margin. Alluvial fans or slopes extend to the playa margin from the Cady and Newberry Mountains; a large north-south trending dune field is present just west of the playa.

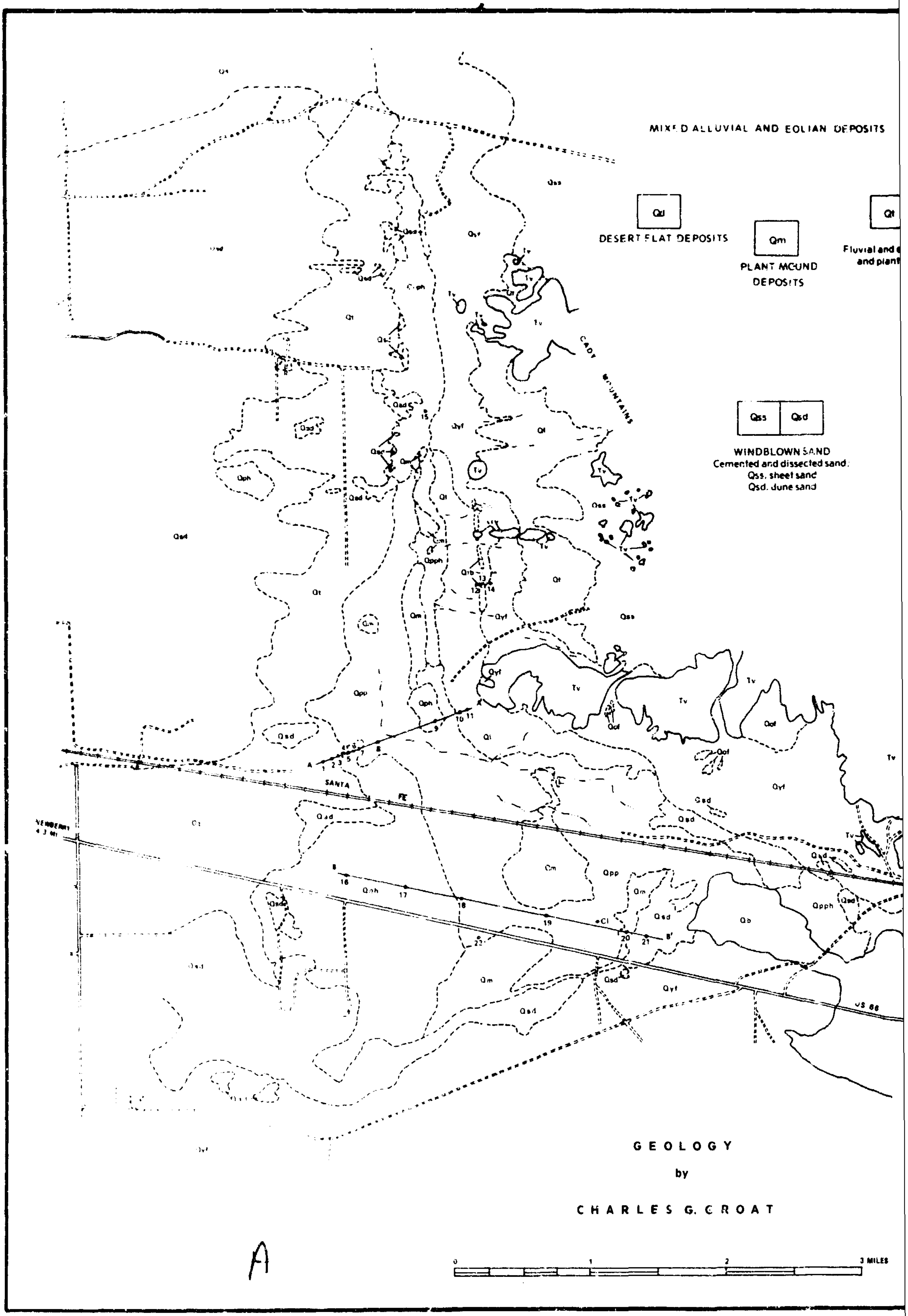
The mountains in the Troy Playa area are composed of Mesozoic (Jurassic?) granite intrustions and Tertiary volcanic and continental sedimentary rocks, all of which have undergone normal and strike-slip faulting, Faulting has

continued intermittently through the Recent producing the present disposition of mountain ranges and basins (Bassett and Kupfer, 1964, p. 38).

The Mojave River, the master stream for the area, crosses the north-central part of the basin; drainage to the Mojave River is separated from drainage to Troy Playa by a broad, low, alluvial divide located just north of the playa. The Mojave River originates in the San Bernardino Mountains southwest of the playa, crosses the north-central part of the Lower Mojave Valley, and terminates at Soda Playa. The channel is well developed, yet flow occurs only after very infrequent periods of greater-than-normal precipitation, and is of short duration.

Drainage into the "sub-basin" occupied by Troy Playa is from the alluvial slopes of the Cady and Newberry Mountains. The slopes are characterized by a roughly parallel system of incised channels 1 to 3 feet deep and 2 to 20 feet wide. They spread and become much less distinct near the toes of the fans, although some channels are slightly incised in some places. A large concentration of channels extends toward the playa from the southeast; however, a basalt flow of Recent age at the east end of Troy Playa has prevented the majority from reaching the playa proper; consequently, fluvial muds and silts have been deposited on the east side behind the flow. Less distinct channels, many blocked by drifting eolian sand, enter the playa from the open basin on the west.

Drainage channels, in the form of very shallow washes 2 to 18 inches deep, are present on the playa and are easily traced on aerial photographs as sinuous, dark-tone ribbons related in part to xerophytic plants commonly present in the channels. Entering the playa from the alluvial slopes, especially from the far eastern end, they wander across the playa, ending in broad, shallow depressions of varying extent (Fig. 1).


MIXED ALLUVIAL AND EOLIAN DEPOSITS
Qd
DESERT FLAT DEPOSITS
Qm
PLANT MOUND DEPOSITS
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Fluvial and e
and plant
Qss
Qsd
WINDBLOWN SAND
Cemented and dissected sand.
Qss, sheet sand
Qsd, dune sand
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GEOLOGY
by
CHARLES G. CROAT
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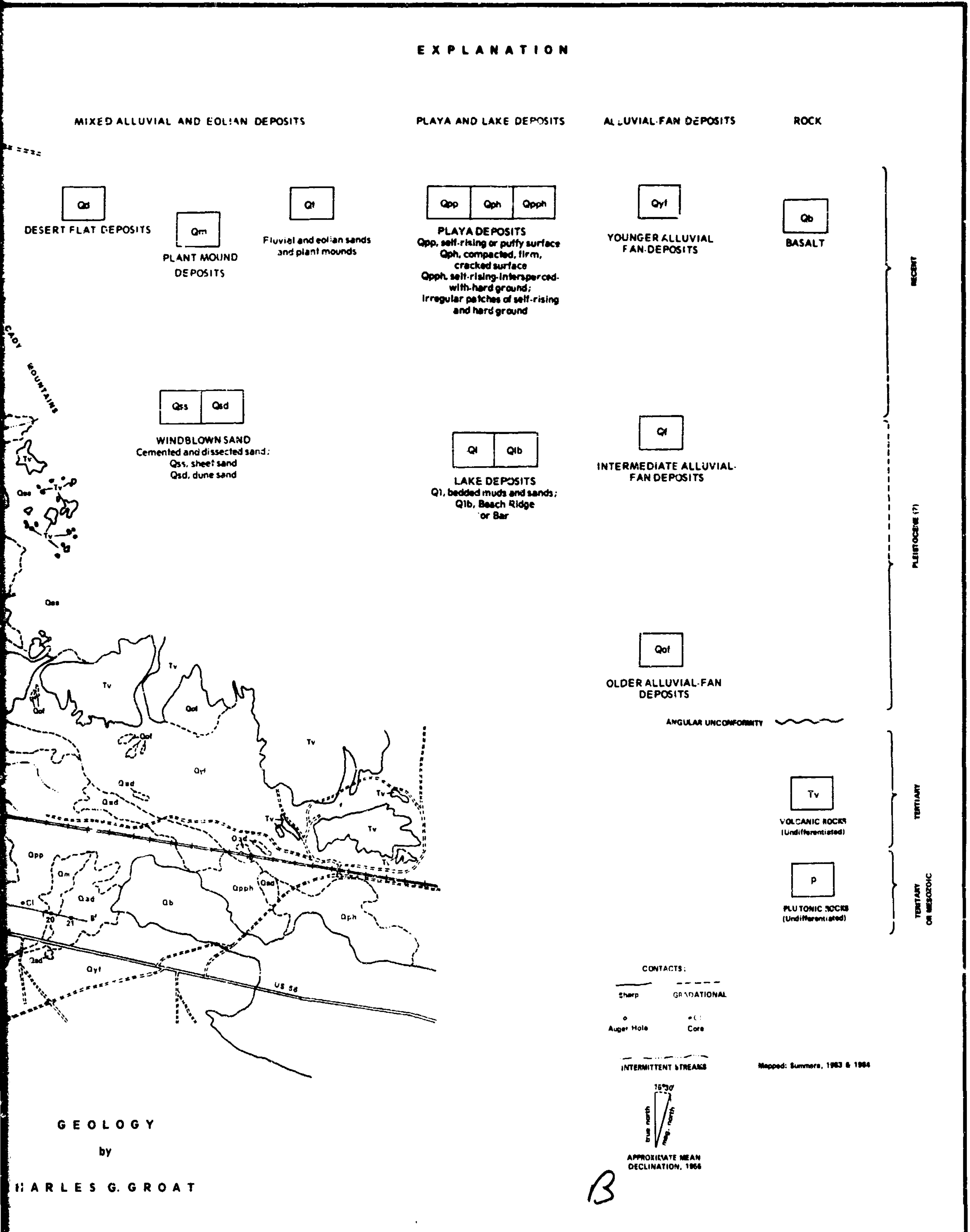


1 2 3 MILES

Figure 1. Geologic map of Troy Playa in 1964.

Climate

The Mojave is a middle-latitude desert characterized by long, hot summers and short, cool winters. Rainfall is sparse and occurs as infrequent, but usually intense storms. In the Troy Playa area thunderstorms usually follow the trend of the Newberry Mountains from west to east around the southern margin of the basin, with the greatest precipitation occurring over the mountains. Runoff down the fans and into the basin and playa area occasionally reaches flood proportions and may cause serious damage to cultivated land and buildings in its path. A storm of this magnitude occurred on August 10, 1963, producing a flash flood which damaged buildings at the base of the Newberry Mountains and flooded parts of the Troy Playa margin south of U. S. Route 66. Rainfall over Troy Playa itself is less frequent and usually less intense; the effects on the playa are significant, however, and are discussed in a later section.

For more information on the climate of the Lower Mojave Valley, the reader is referred to Chapter 3, Part 1.

GEOLOGY OF TROY PLAYA AND ADJACENT AREAS

The uppermost sediments of Troy Playa were deposited in ephemeral playa lakes, whereas at least part of the deeper sediments were deposited in a relatively permanent lake, Lake Manix of late Pleistocene age. A bar or beach ridge and associated lake sediments, deposited in Lake Manix, are present along the eastern margin of central Troy Playa. Alluvial-fan detritus from the Cady and Newberry Mountains (Fig. 4, Chap. 1; Fig. [illegible], this Chap.) interfinger with playa and lake deposits near the playa margins. Dunes flank the playa on the west and south; windblown sand also interfingers with alluvial-fan deposits on the west-facing slopes of the Cady Mountains where sheets of windblown sand are prominent. The windblown sand is all younger than the Lake Manix deposits. The terminal part of a basalt flow of Recent age, a product of Pisgah crater 11 miles southeast of Troy Playa, overlies playa sediments near the southeast margin of the playa. Groat (1967) discusses the deposits and features listed above, plus their interrelationships and geologic history, in considerable detail; however, this report will be concerned primarily with lake sediments and playa sediments.

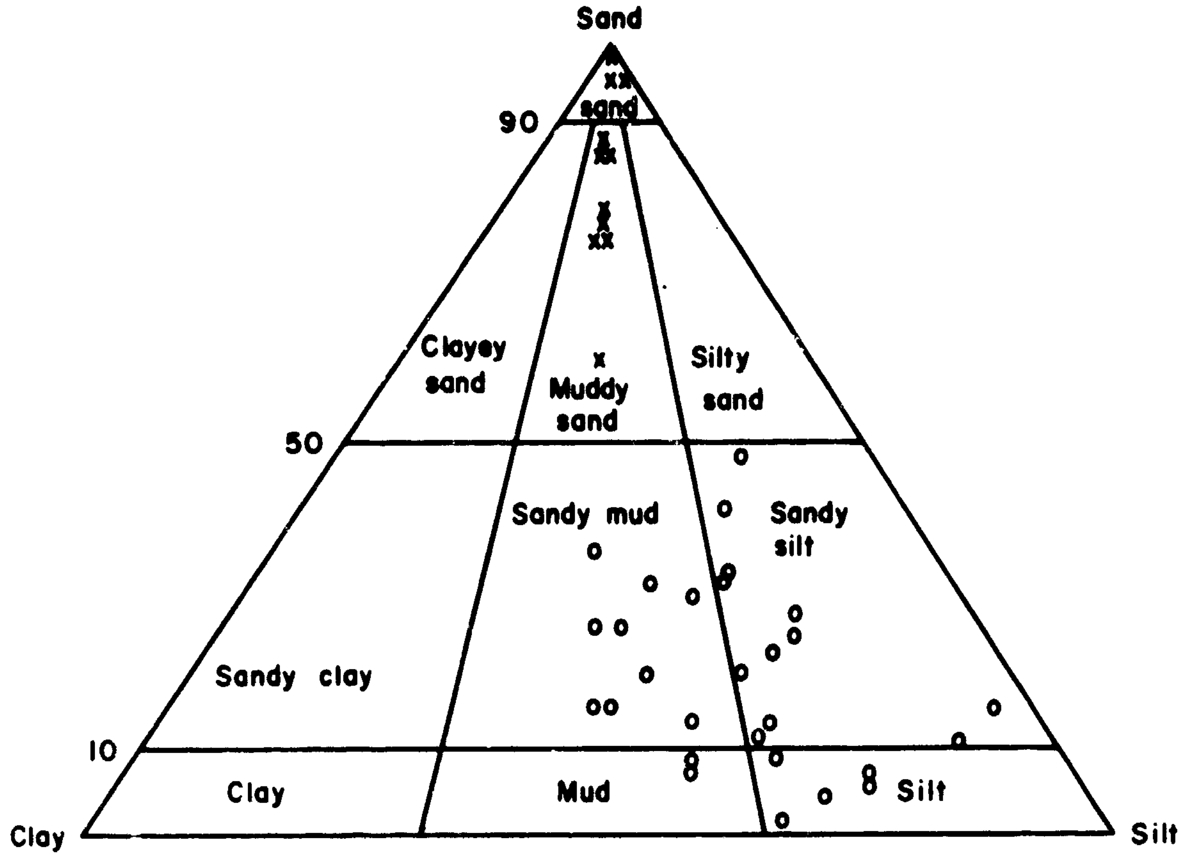
Lake Sediments

The lake sediments are exposed in a continuous band at the toes of alluvial fans flanking the Cady Mountains; the best exposures are at the southwest corner of these fans. In this area the lake sediments are truncated near the playa margin and stand 1 to 5 feet above the playa surface. Erosion by washes graded to the playa and by the wind has created a hummocky topography characterized by mounds and shallow depressions. The mounds are topped by plants whose roots have protected parts of the sediments from erosion. Where

exposed, the bedded, brown, lake sediments are muddy sands, sandy silts, and sandy mud. "Mud" and other grain-size nomenclature are used as Folk (1964, p. 27, and 1954, p. 359) has defined the terms (Fig. 2). "Mud" implies that both silt and clay are present; the term "clay" is used where high plasticity indicates that clay is dominant.

The moderately to poorly sorted sands occur as distinct beds, 1 to 2 feet thick, and are interbedded with sandy muds. Near the southwest corner of the Cady Mountains the lowermost sands are interbedded with and overlie a brown, plastic clay similar to that penetrated in the playa at depths of 1 to 6 feet. The similarity of these clays and their stratigraphic positions suggest that they may be correlative, at least in part; in other words, both deposited in the shallow arm of Lake Manix that occupied the Troy Playa area during late Pleistocene time. The silt and mud above this clay in the playa area are interpreted as ephemeral-lake or playa deposits; these muds and the brown clay comprise the mud facies described in the following section.

The exposed lake sediments were deposited in a near-shore environment, for they interfinger with the sand of the prominent bar or beach ridge that is present along the eastern margin of the central playa. The top of the bar or beach ridge and the eastern limit of the lake sediments behind it are approximately 1,795 feet, the same elevation as the bars and shore features associated with late Pleistocene Lake Manix in the Afton Canyon area (Blackwelder and Ellsworth, 1936, p. 459). Dibblee (1963) also believes that the lake and bar or beach-ridge sediments were probably deposited in Lake Manix.



o Analyses of mud facies by Halpin (1965). See Fig. 1 for location of core C1

x Analyses of sand facies (this report): No attempt was made to separate the mud fraction into silt and clay hence the results are plotted axially. Points falling in the sand area are the granular upper portions of the sand facies that resemble modern desert-flat lag deposits.

Figure 2. Analyses of sediments from Troy Playa.

Playa Sediments

The upper 10 to 15 feet of playa sediments were studied in detail by logging of auger holes and trenches in the field (Fig. 3). The depth of auger holes was limited by the water table, for once it was reached, caving of the holes resulted. I determined the ratio of sand to mud (silt plus clay) for 12 samples and Halpin (1965) determined the ratio of sand, silt and clay for 28 samples from a 116-inch continuous core taken in southeastern Troy Playa (Fig. 3). The results of these analyses are shown on Figure 2. From the field and laboratory determinations two facies were delineated in the sediments underlying the upper part of Troy Playa: a mud facies and a sand facies.

Mud Facies

The surficial sediments of Troy Playa from 1 to 15 feet beneath the surface are sandy mud, sandy silt, mud, silt, and clay. These are grouped together as the mud facies. Sediments of the mud facies are generally medium brown to slightly reddish brown. Gray and greenish-gray sandy muds a few inches thick were penetrated at or below the top of the ground-water saturated zone. Whether the gray color is due to reducing conditions in the saturated zone or related to the environment of deposition is not known.

The uppermost 1 to 6 feet of playa sediments are silt, sandy silt, mud, and sandy mud (Fig. 3). Brown, moist, plastic, silty clay occurs beneath these sediments in the central area of the playa where the clay is interbedded with and grades into the overlying sediments. The clay is gritty due to scattered grains of fine and medium sand. This clay is very similar, and perhaps correlative, to the clays interbedded with and overlain by the sands of the lake deposits.

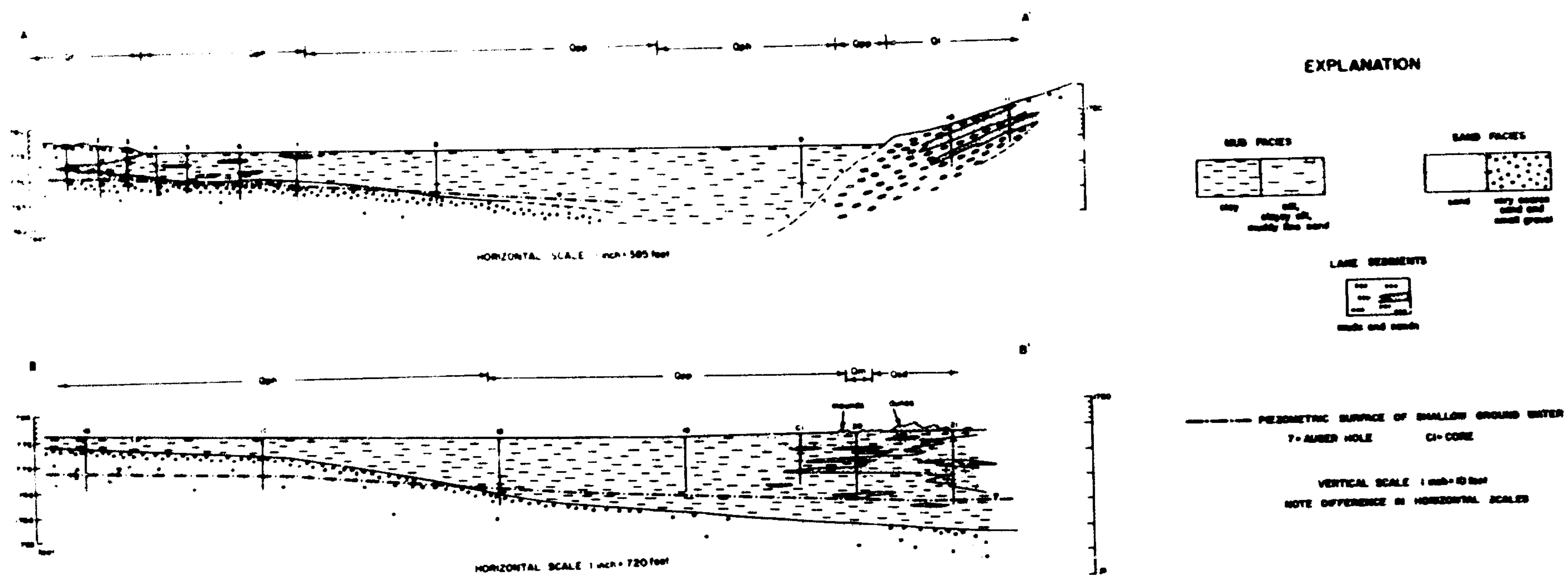


Figure 3. Cross-sections of Troy Playa. For locations of sections, see geologic map (Fig. 1).

Droste (1961, p. 13) analyzed four samples of clay from Troy Playa and found montmorillonite, illite, and chlorite in a ratio of approximately 5:4:1. Droste concluded that weathering of source rocks could adequately account for the assemblage. Kerr and Langer (1965, p. 61) analyzed a bulk crystal sample from Troy Playa and found kaolinite in addition to the clay minerals reported by Droste. Kerr and Langer also found that quartz and feldspar are the chief granular components of Troy Playa.

Sand Facies

Sand is present beneath the mud facies near all margins of the playa. The sands are texturally immature because they contain more than 5 percent clay matrix (Folk, 1951, p. 128); however, three samples of granular, coarse sand contain less than 5 percent mud. Most samples are also mineralogically immature and they contain abundant fresh, angular orthoclase which commonly is more abundant than quartz. Granitic and felsic-volcanic rock fragments, constituting from 2 to 10 percent of the sand, are more abundant in the coarser and granular sands. Biotite and muscovite constitute 1 to 5 percent of the grains and are most abundant in the fine fraction.

The upper several inches to 1-1/2 feet of the sand, in most places, is coarse to granular, better sorted than the underlying finer sands, and contains only 5 percent mud. Frosted grains are present in these coarser portions. Mineralogically and texturally this sand resembles the upper or lag sand of the desert flat and lower fan surfaces (Groat, 1967, Table 1). The sediments below this distinct coarse to granular sand vary in grain size from very fine to coarse sand, and vary in mud content from 13 to 43 percent. Some mud lenses are present in these lower sands.

The muddy sands were probably deposited near the margins of an ephemeral playa lake by sediment-charged streams and in the shallow lake itself as broad sheets formed when the dense sediment-water mixture spread out across the lake bottom. The sands are very similar to those of the lowermost parts of alluvial fans emerging from the Newberry Mountains and are probably of similar origin. The coarser, lag-like upper sands may have resulted from eolian reworking of these desert-flat or alluvial-fan deposits which produced a coarse sand and granule lag similar to that present in these environments today. Increased flooding frequency could subsequently have expanded the playa over the alluvial-fan or desert-flat sands.

Facies Relationships

Examination of the sediments near the playa margins showed that although the contact between playa muds and alluvial-fan sands appears sharp, it is actually gradational. The sands of the lower fans are muddy near the playa and become more gravelly toward the mountains. Likewise, near the playa margin the playa muds contain lenses of sand and sandy mud with sandiness decreasing toward the playa (Fig. 3).

Subsurface data demonstrate that the boundary between the playa environment and surrounding environments has not remained stationary but has fluctuated during all stages of playa development. West of the playa, in the transition zone, playa muds extend westward beneath the sands (Fig. 3). A similar condition exists along the southern margin of the playa where the alluvial fans of the Newberry Mountains are in contact with the playa muds (Fig. 1). Beneath the playa mud and extending toward the playa is a wedge of sand (described above) with a characteristic coarse or granular upper portion. This sand probably represents a former expansion of lower fan or

desert-flat conditions into the area that is now playa, whereas the mud above represents a subsequent expansion of the playa toward the fans and desert flat. At the playa margins this mud is overlain by sandy material of the modern fans and desert flat.

These facies relationships indicate that the geographic extent of fans, desert flat, and playa has varied in the past. As the geographic extent of fluvial and eolian deposition has increased, the area of shallow-water or playa deposition has been forced toward the center of the basin. Conversely, environmental factors favoring broadened playa deposition have concurrently caused a retreat or regression, at least in some areas, of the sandy, fluvial, and eolian facies.

Microplayas

Small (10 to 50 yards in diameter) playa-like features or microplayas are scattered throughout the transition zone (Fig. 4). Near the playa they are merely areas where windblown sand has irregularly covered parts of the playa or deflation has removed the windblown-sand cover from its western edge. Further west, in the transition zone, microplayas are isolated from the main playa surface and have formed in shallow depressions where runoff from rainstorms has accumulated and evaporated, leaving a residue of mud. Several of these features were investigated and one was trenched along several radial lines to determine their origin and relation to the playa (Fig. 5). Sands surround and underlie many of the microplayas of the western transition zone, attesting to their independence from the main playa. The presence of both types of microplayas and the interfingering of desert-flat sands with playa sediments indicate that this area is truly a transition zone in that playa-like sedimentation and desert-flat or dune-field conditions are intermixed.

Figure 4. Microplaya in the transition zone northwest of Troy Playa.

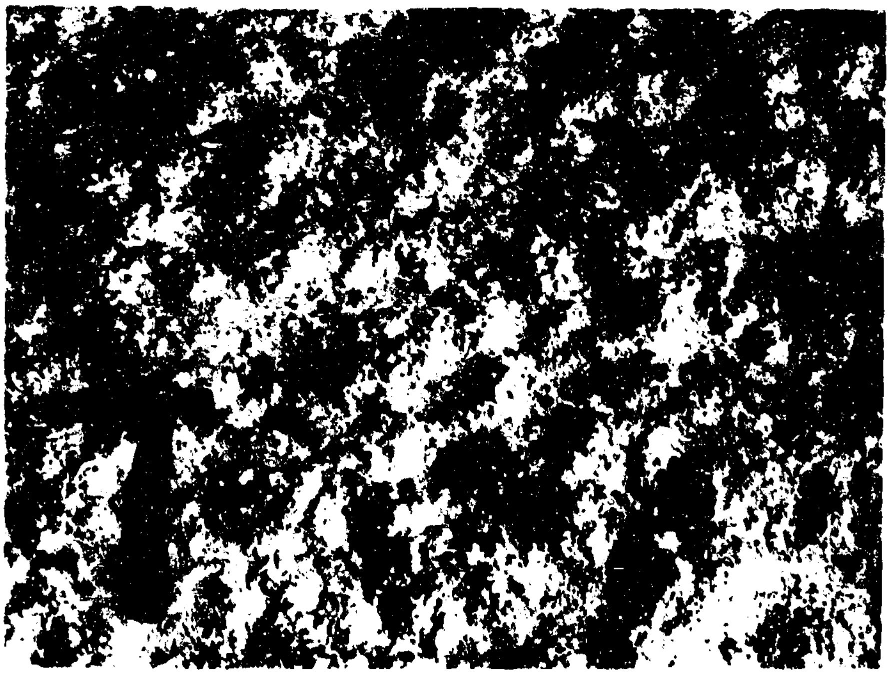


Figure 6. Puffy ground of south-central Troy Playa. Note the salty crust.

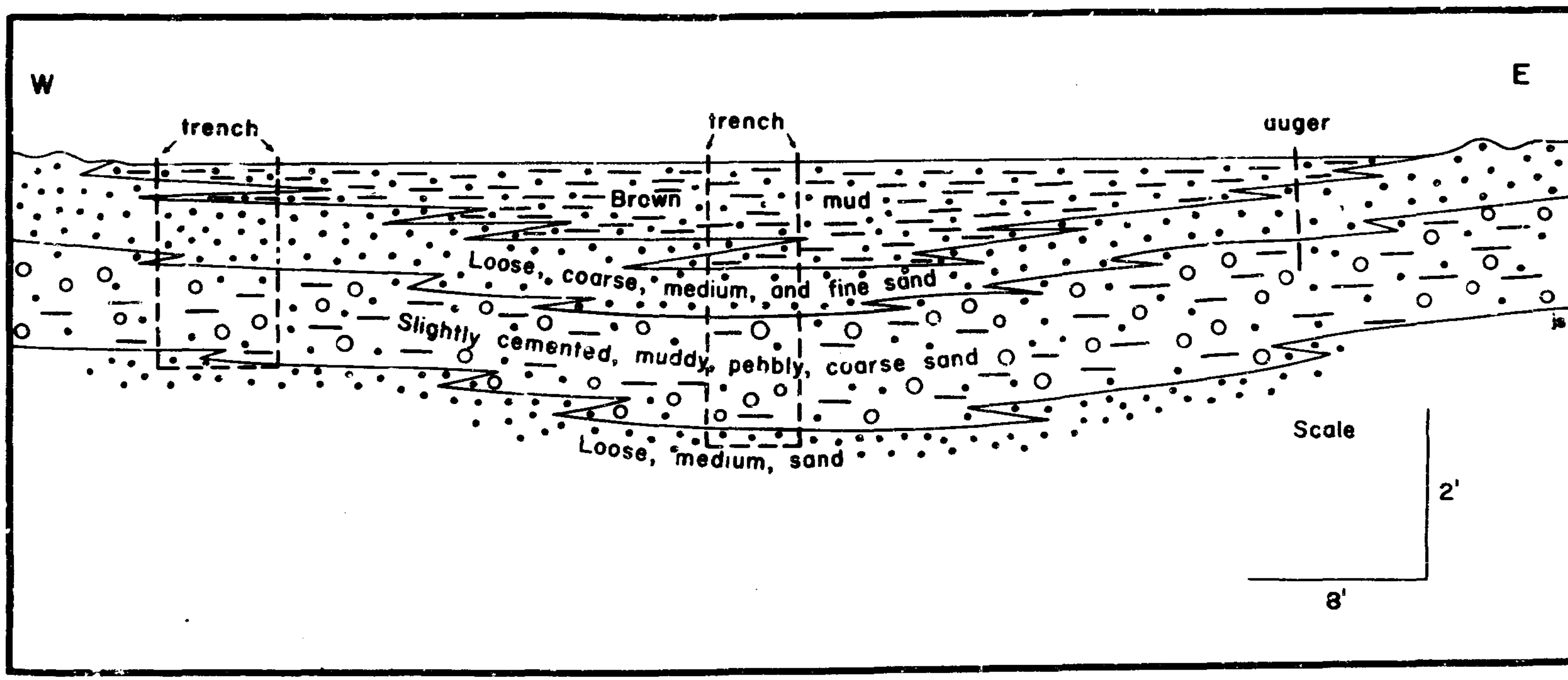


Figure 5. Cross-section across microplaya photographed in Figure 4.

Several of the microplayas and parts of the desert flat are furrowed or blown-out. Many of the plant mounds are extensively dissected and, in some places, only stubble with faint traces of the former mound remains. It appears that the mounds and portions of the desert flat and sand dunes are being gradually removed by the wind and that the plants are dying, thereby losing their ability to support their shadow sands and silts. Considering the dissection shown in the dune-fields and that in the transition zone, the formation of the depressions in which microplayas have developed can best be explained in terms of deflation of desert-flat and dune sands. During arid periods, such as the present, eolian deposits accumulate but erosion is also prominent. Depressions form, and commonly become depositional sites during rain storms or more prolonged wet periods. The two processes, deflation and deposition in the depressions that deflation forms, are dynamic ones and the sites may shift. Thus while some microplayas may endure, othere become covered with drifting sand. The deflation of sands and plant mounds, and subsequent or nearly contemporaneous deposition of muds could account for considerable expansion of the playa. The merging of microplayas and removal of remaining mounds could create expanses of uninterrupted playa surface. Motts (Chap. 7, p. 270) has concluded that Rabbit Playa, California, and other western playas have also been expanding, but by different mechanisms than those discussed here for Troy Playa.

Plant Mounds

Conical mounds, 1 to 3 feet in height, occur individually or in groups over parts of the Troy Playa surface. Sediments in the mounds vary in texture; silty sand and sand are common, but silt and clay mounds are also present. The mounds may be structureless "piles" of sediment or consist of a stratified core of firm, commonly moist sediment, overlain by loose silt, sandy silt, or sand. Mound surfaces are either hard or exhibit the puffy or self-rising appearance characteristic of much of the playa. Dead or dying plants top or partly cover most of the mounds. Most of the mounds are partly dissected and in some areas they have been nearly removed by the wind. The ground between the mounds may be flat or irregular and hummocky.

The plant mounds resemble those formed in the lake deposits and transition zone. The mounds on the playa are very similar to those in the lake deposits immediately west of the beach bar and are separated from them by only a narrow strip of featureless playa. This mound area may have been continuous with the lake deposits at one time and the wind and/or wash-channel activity might have removed parts of the mounds. Playa sedimentation could then have resulted in the flat playa surface now present between the areas.

Motts (1965, p. 89) has found similar mounds on other playas in the Mojave Desert and has termed them "phreatophyte mounds." He believes many originate by wind-deposited sediment, accumulating around the roots of phreatophytes and attributes the puffy crust to the discharge of water around the plants. This explanation seems partly correct for the Troy Playa mounds, but in addition to accumulating sediments, the roots of the plants on the lake deposits have protected portions of these sediments from

deflation. This type of protection is probably a factor in the development of plant mounds on the playa sediments as well, for the puffy ground of the playa is subject to deflation and the roots of the phreatophytes offer protection. Lowering of the playa surface by deflation could increase the relief of the mounds.

The condition of plant, or phreatophyte, mounds can serve as an indicator of ground-water conditions in playas characterized by a shallow water table and relatively coarse-grained sediments. The presence of eroded mounds topped by dead plants may indicate a decline of the shallow water table or deterioration of ground-water quality, whereas aggrading mounds, topped by healthy phreatophytes, may indicate ground water of relatively low mineralization near the land surface.

TROY PLAYA SURFACE

Playa Surface Types in 1964

Troy Playa, as mapped in 1964, consists of three surface types: (1) knobby-soft or puffy ground consisting of a thin crust of compacted clay or silt underlain by several inches of loose silt--in places, this material has a crust of salt, chiefly halite; (2) a hard-compacted surface of mud-cracked clay and silt; and (3) puffy ground interspersed with hard-compacted ground.

Puffy Ground

Puffy ground occupies the largest and most continuous surface area of Troy Playa. The surface is rough and welted on a small scale (Fig. 6), with a 1/2 to 2 inch thick crust that is either porous and "honeycombed" or compacted and underlain by 2 to 6 inches of dry, loose silt.

The crust is a light buff-brown color and is lightly dusted with sand grains. It is composed of clayey silt and evaporite minerals (chiefly halite) and is easily broken through when walked on or driven over (Fig. 7). Laboratory tests to determine the percentage of water-soluble salts were made by weighing a sample of the crust, adding water and shaking, decanting the solution, and drying and weighing the residue. The wetting and decanting were repeated two or three times. The amount of water-soluble material in the crust varies from minor to nearly 75 percent; the most common example lies between the extremes, but distinctly salt-encrusted or glazed ground is present over parts of the playa (Fig. 6).

The underlying loose silt is "granular," dry, and commonly contains salt needles and flakes. The individual particles may also be silt-sized

Figure 7. Automobile tracks on puffy ground.

Figure 8. Hard-compacted ground in the southwestern part of Troy Playa.

and fine-sand-sized flocculated aggregates of silt and clay. This material reacts violently with dilute hydrochloric acid, indicating a high carbonate content. The presence of this loose material causes walkers and vehicles to sink into the playa surface to a depth of a few inches (Fig. 7). The compacted muds beneath the loose silt are firm and moist, becoming moister and more plastic with depth.

Plants are very sparse or absent on most puffy ground; however, salt grass covers parts of the southern margin of the playa and occurs in patches in other areas. Pickleweed and salt bush occur as individual, isolated plants in some places.

Hard-Compacted Ground

Hard-compacted ground displays a characteristic compacted surface and polygonal fractures or mudcracks. Silt or clayey silt occurs in the upper few inches and in many places the upper 1 foot or more of sediment is compacted, dry, and impermeable. In some places, notably near the contacts between hard ground and puffy ground, the compacted part may be only an inch or two thick and underlain by relatively looser sediment. The polygons between mudcracks vary from 2 to 8 inches in diameter and are developed most prominently where the compacted crust is thickest (Fig. 8). More than one generation of cracks may be present. Cracks may be distinct and penetrate 1 or 2 inches or may be partially filled and indistinct (Fig. 9).

Unlike hard-ground areas of dry playas, much of this surface on Troy is covered with plant growth nearly as dense as that of the desert flat. This is especially true in the southwestern part of the playa where the compacted crust is 2 to 4 inches thick or less (Fig. 10). In localized hard areas the

Figure 9. Partly filled mudcracks on Troy Playa.

Figure 10. Plants, chiefly xerophytes, on the southwestern part of Troy Playa.

hard ground is interrupted by patches of puffy ground, particularly where plant growth is most dense. In these areas the remains of salt bush and pickleweed are commonly found.

Puffy Interspersed with Hard-Compacted Ground

Troy Playa has large areas of puffy ground interspersed with hard-compacted ground. Significantly large areas were mapped in this way because it would have been impractical to trace out each hard or self-rising zone. This surface is best developed in the northern part of the playa, primarily because a large number of washes reach the playa from the alluvial fans to the east. Some puffy interspersed with hard-compacted ground also occurs where clay and silt, washed from the puffy ground itself, has accumulated in low adjacent areas. In these depressions where the clay and silt is very thin (1 inch or less thick) capillarity has destroyed the mudcracked pattern and imposed a puffy surface type.

Development of Playa Surface Types

The surface types on Troy Playa, according to my interpretation, are determined by delicate relationships involving the configuration of the top of the shallow saturated zone or water table and the stratigraphy of sediments underlying the playa. The reasons for this interpretation are set forth below.

Augering showed that the upper 1 to 15 feet of sediment in Troy Playa are silt, sandy silt, mud, sandy mud, and clay (see previous section on playa sediments and Figs. 1, 2, and 3). This body thins in all directions from the center of the playa, but most gradually toward the west (Fig. 2). It can also be seen from Figure 3 that the puffy ground is most coincident in aerial extent with those areas underlain by the thickest parts of the mud body.

A traceable sand unit is immediately beneath the mud body. This unit, approximately 10 feet thick near the playa margins, thins as the mud body thickens toward the center of the playa (Fig. 3). Beyond the playa the sand merges, in an upward direction, with the sands of the desert flat and dune areas. Coarse and very coarse sand is dominant with varying thicknesses of medium sand constituting the remainder of the unit. The sand is moderately sorted (field determination) although silty lenses are present. A more complete description of these units is presented in the previous section on playa sediments.

It is the location of the shallow water table in the playa sedimentary sequence that controls the playa surface type. Where the water table is within the sand unit; that is, where there is unsaturated sand between the potentiometric surface and the mud unit above the sand, the playa displays

a hard-compacted surface (Figs. 3 and 8). Where the water table is within the mud unit and the underlying sand unit is completely saturated, the playa surface is puffy. Where the latter condition prevails, the capillary zone extends to the playa surface and discharge of ground water occurs. In the areas where unsaturated sand is present beneath the mud unit, because the upper part of the mud unit is dry, the capillary force is lost in the porous sand and the capillary fringe does not extend to the surface (Fig. 3).

The height of capillary rise in sediments is controlled by the diameter of the interstices between the grains. In general, the narrower the interstices, the greater the height of rise (Todd, 1959, p. 22). In the Troy Playa sediments, the height of rise in the more compact mud unit is much greater than that in the much coarser, better sorted, coarse sand. Thus where the mud unit is within the saturated zone the height of capillary rise is much greater than where the top of the saturated zone is within the sand unit. As the thickness of sand between the top of the saturated zone and the bottom of the mud unit increases, the height of capillary rise into the overlying mud body decreases.

Field investigations, including extensive augering, revealed that the contact area of the puffy ground with the hard-compacted ground coincides very nearly with the place or zone where the saturated zone enters the sand body and that hard ground becomes best developed in the direction of thickening of the sand unit (Fig. 3). Augering in these hard areas of the playa where the saturated zone's upper boundary is well within the sand unit also showed that the foot or two of compacted silt beneath the playa surface was completely dry or only slightly moist, and that the sand above the saturated zone and below the mud was only slightly moist. In areas of puffy ground, where the saturated zone extends into the mud unit above the sand, the

sediments were very moist up to the base of the loose silt that is present immediately beneath the thin clayey silt or salt crust. The sand unit, therefore, acts as an impasse to capillary rise from the saturated zone. If not completely halting capillary rise in all places, the sand at least reduces drastically the amount of water transported upward by this mechanism. I interpret these interrelations between the saturated zone and stratigraphy to be the primary determinative factors that have produced the present surface types on Troy Playa.

Based on the conditions that control the present surface types on Troy Playa, described above, it is possible to relate past or future changes in the configuration of the potentiometric surface and shallow water table to changes in the distribution of playa surface types, or vice versa. A rise in the potentiometric surface and consequent rise of the shallow water table would saturate the mud unit beneath a greater area of the playa surface. Capillary discharge of ground water would then occur in areas presently exhibiting a hard-compacted surface and the hard-compacted surface would eventually be converted to a puffy surface. Conversely, a drop in the elevation of the potentiometric surface would cause the water table to lower and enter the sand unit in areas where it is presently in the mud unit. This would result in an expansion of hard-compacted-surface morphology toward the center of the playa, an area presently characterized by a puffy surface.

In areas where capillary rise of ground water to the surface is not sufficient to produce a puffy surface, the dominant effects are surface inflow, rainfall, and desiccation. Puffy ground is a type which develops in opposition to these atmospheric phenomena that, in the absence of capillary discharge, would normally produce a hard-compacted-surfaced playa. Any

decrease in capillary discharge, therefore, allows the alteration of a puffy surface to a hard-compacted surface and any increase could conceivavably do the opposite.

Factors other than the configuration of the potentiometric surface can affect the surface morphology of a playa. A relatively high frequency of flooding of the playa surface, or high flooding ratio (Motts, 1965, p. 76), would promote significant sediment accumulation. Continued deposition and desiccation could obscure the effects of a high water table and result in a hard-compacted rather than puffy surface. This may have occurred during the past, but under the present arid regime, sedimentation at Troy Playa is negligible.

Hard ground is primarily the result of alternate wetting or flooding and subsequent desiccation of the playa surface. Where there is no moistening of the upper few feet of sediments by capillary rise, the desiccation may extend downward several feet resulting in deep, large polygonal cracks. Development of hard-compacted areas in previously puffy parts of Troy Playa has occurred and is occurring as follows:

(1) Runoff from storms enters the playa in numerous washes from the Cady and Newberry Mountains, collecting in broad, shallow depressions in the playa surface. The majority of these depressions are in the northern portion of the playa, and the largest is in the north-central section. A major wash, readily discernible on aerial photographs and mapped (Fig. 1), enters the playa from the east; one branch enters this depression while the other continues west and finally swings north. Flooding and minor deposition of muds in the depression, and their subsequent desiccation, have produced the elliptical hard-compacted area present there (Fig. 1). As this hard-compacted area is surrounded by puffy ground, it is inferred that the fre-

quency of flooding has been sufficient and the concentration of runoff water has been of sufficient volume to compact the puffy surface, resulting in a desiccated, compacted crust that has resisted destruction by capillary discharge. Deposition has raised the floor of the depression and erosion in the main wash channel has lowered the channel bottom to the extent that the branch that fed the low area is no longer active and runoff follows the other segment into an adjacent area. This process has occurred on a smaller scale at the mouths of washes and in localized depressions in other parts of the playa, notably the northern section mapped as "puffy interspersed with hard-compacted ground" (Fig. 1). In some places in this area it can be observed that evaporation from the capillary fringe is destroying the mud-cracked surface, forming puffy ground at its expense. The desiccated crust in the small, shallow depressions not fed by washes, but fed from the surrounding playa, is only 1/4 to 1/2 inch thick and easily destroyed.

(2) In the western and southwestern parts of the playa, where the sand units interrupt the capillary rise of ground water, wetting and desiccation of the surface has produced a hard-compacted surface that has not been modified by capillary discharge, because the relation of the sand body to the saturated zone has rendered capillary rise impotent. Desiccation has produced a compacted, dry zone 1 to 2 feet thick and, in places, a pronouncedly cracked surface.

These processes of conversion from puffy to hard-compacted grounds are accelerated by a current decline of the potentiometric surface. The decline in water levels throughout the Lower Mojave Valley is clearly indicated by data compiled by Dyer and others (1963).

The isolated patches of puffy ground that are present in the hard-compacted area west of the playa can be related to the mode of development

of the hard ground there. Much of the hard-compacted ground of Troy Playa probably has formed at the expense of puffy ground in response to the lowering of the head of ground water in the shallow aquifers in the area. The decrease in capillary discharge has allowed flooding and subsequent desiccation to foster the development of hard-compacted ground. The isolated patches of puffy ground are relics from the former period of discharge or, in some places, may be related to lenses of fine sediment where capillarity is yet effective.

Kerr and Langer (1965) have de-emphasized the role of ground water in determining playa surface type and have stressed the importance of sediment size and composition. They analyzed 27 samples from 16 representative Mojave Desert playas and found that the crusts of puffy playas contained coarser sediments and more salts than those of hard-compacted playas. They concluded that the more clay-rich, hard-compacted playas were less permeable to runoff and that desiccation produced mudcracks, whereas the wetting of more granular, salty crusts induced swelling and the formation of a puffy surface.

It is possible that the coarseness of puffy crusts is a determinative factor; however, the coarseness may be a result of the puffy surface rather than a cause of it. Deflation of puffy surfaces occurs and has been observed on Troy Playa. It can be argued that this deflation has selectively removed the finer particles from the puffy areas, increasing their relative coarseness. A hard-compacted surface resists deflation and winnowing is not prevalent. Evaporation from the capillary fringe of a high water table provides a ready source of salts and of moisture for swelling. The unmistakable association of high water tables with puffy surfaces (Thompson, 1929; Stone, 1956) suggests that the presence of shallow ground water is an important factor in the development of a puffy playa surface. Puffy crusts may endure beyond the

time when capillary discharge declines, preserved by wetting by rainfall, but leaching by downward percolation could eventually remove the salts thus inhibiting swelling.

Effects of Surface Runoff on Morphology of the Playa Surface

The effects of two rainstorms over the playa, one in August 1963 and the other in July 1964 were noted in some detail. Other changed, produced by surface water, are discussed in Chapter 7 of this publication.

The first rainstorm was a light rain that produced no lasting effects. It was noted, however, that 1 to 2 inch deep pools of water were left standing in areas that were previously mapped as hard areas in the puffy-interspersed-with-hard-compacted-ground part of the playa. This rain failed to disrupt the structure of the puffy ground; in fact, downward moisture penetration did not exceed one inch. The mudcracks of the hard-compacted ground filled with water whereas the clay plates they bounded were not submerged. Clay settled into the cracks, partially filling them (Fig. 9) and upon desiccation new cracks formed. In the microplayas of the transition zone and in parts of the hard areas where water stood to a depth of 3 inches, the surficial playa muds were put into suspension. These settled out and, after desiccation, peeled back as 1/8- to 1/4-inch-thick plates. Since these plates were not present when the area was revisited in 1964, it appears that they were removed, probably by deflation, during the interim.

The effects of the second observed rain, a more intense storm, were more pronounced. The major east-west wash on the playa surface carried water westward across the playa, past the cut-off leading into the large elliptical hard area of the north-central playa, and into an area about 300 yards west of this hard-compacted ground (Fig. 11). This body of standing water, 6 to

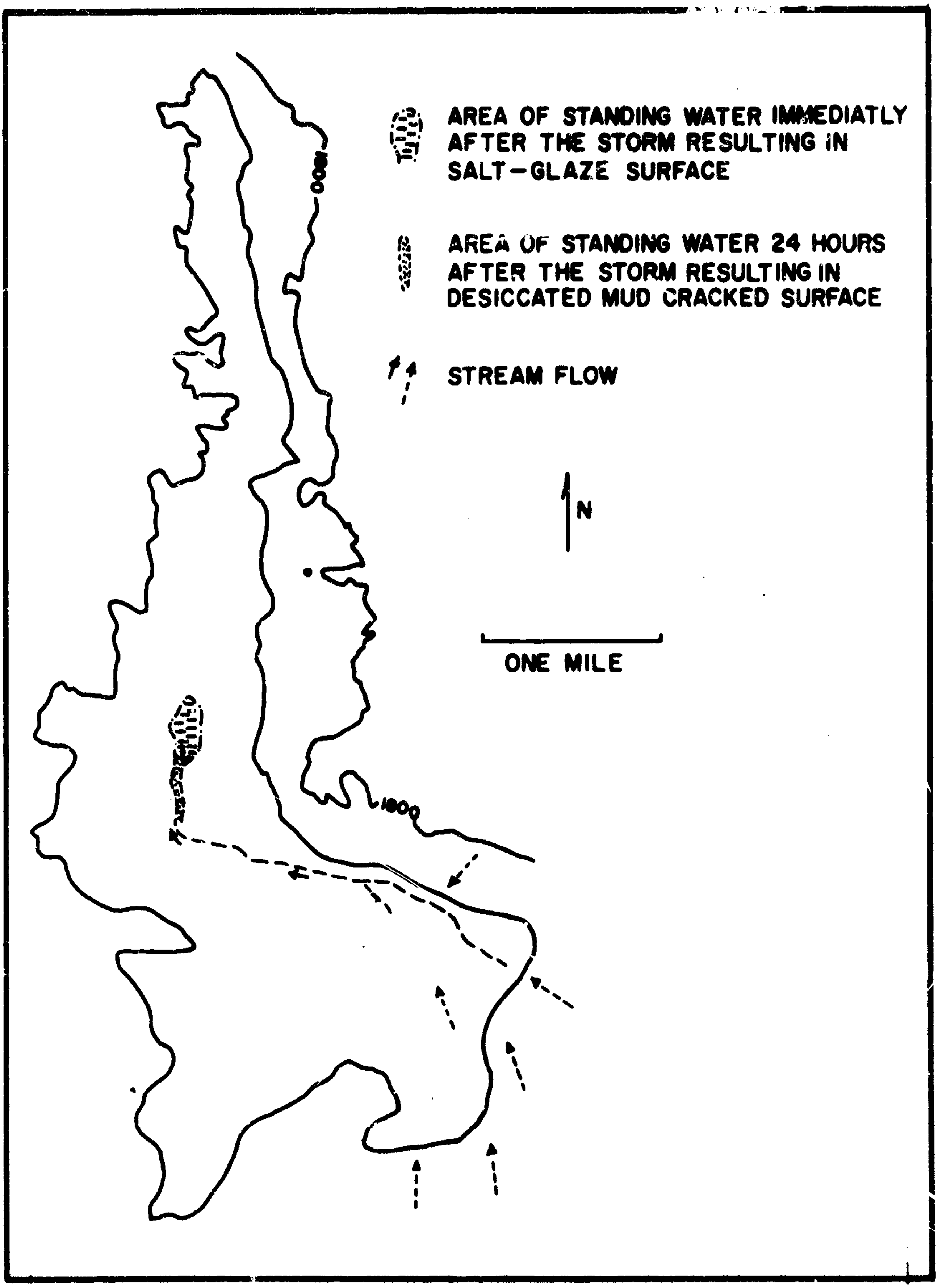


Figure 11. Map of Troy Playa showing areas of standing water resulting from July 1964 storm.

8 inches deep at the center, covered an area at least 100 by 200 yards on the puffy ground. Upon drying, the marginal areas remained as before, but with a 1/8-inch thick glaze of salt over the surface. The central area, where water was still ponded 24 hours after the storm (Fig. 11), became desiccated and mudcracked (Fig. 12).

In the southern part of the playa, south of the Santa Fe Railroad tracks, the puffy ground was thoroughly wetted although water was not ponded. Upon desiccation the welted, cracked surface present before the rain altered to a smoother, if uneven, character. Salts, previously mixed with the clayey-silt crust, were dissolved by the rainwater and were left, upon evaporation, as a 1/8- to 1/4-inch-thick white coating spread over the entire area of puffy ground (Fig. 13). This gave the surface a completely different appearance from the pre-existing light brown to buff color. Small solution pits, 1 to 2 inches in diameter, were also observed. These were similar in nature to those present on the salt-encrusted puffy ground of Bristol Playa (visited during 1964), although not as numerous. Auger holes were put down in this area of Troy Playa to see if these solution pits were the result of downward percolation of water. Fine and medium sand lenses in the mud unit were saturated with perched water and the entire unit was very moist to a depth of at least 15 feet. Previous to the storm the unit was quite moist; however, the perched water zones were not present. This indicates that during and after intense rainfall the puffy ground is an area of considerable downward percolation of water.

Auger holes were also made in the hard-compacted ground of the western part of the playa and observations compared with those made before the rain. It was noted that the mud unit beneath the surface had remained dry and no change in the moisture of the sediments had occurred. The surface exhibited

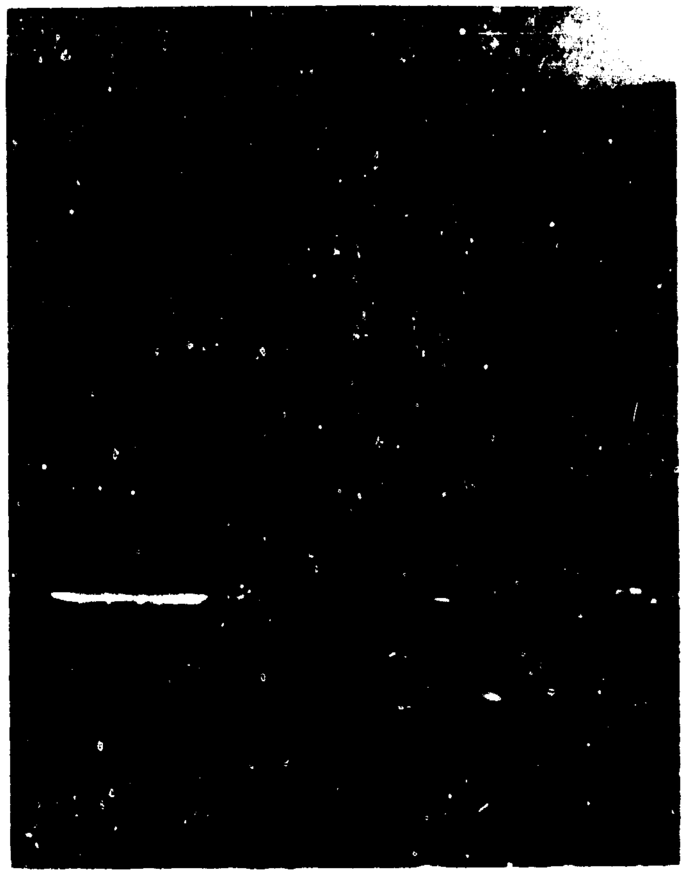


Figure 12. Partly desiccated puffy ground covered by standing water after July 1964 rain. Note developing mudcracks. Photograph taken 3 weeks after the rain.

Figure 13. Salt-glazed surface resulting from July 1964 wetting Troy Playa surface; southeastern part.

a new generation of mudcracks, some of which were concave-upward polygons, 1/4 to 1/2 inch thick, that lay on the surface as plates.

As previously stated, under conditions of decreased capillary rise of ground water and evaporation at the surface, playa floodings and desiccation could convert puffy ground to the hard-compacted surface type. Destruction of very thin and localized hard-compacted areas within the puffy areas by evaporation from the capillary fringe does occur at Troy, but the presence of the large elliptical hard-compacted area and others of seeming permanence within the confines of puffy ground indicate that the process of surface change may be occurring on Troy.

GEOLOGY OF TROY PLAYA SURFACE, WINTER OF 1967-68

by

Ward S. Motts

Remapping of the surface of Troy Playa in January and February of 1968 showed that the morphology of the playa surface had changed considerably from 1963 and 1964 when Groat mapped it (Fig. 14).

The most striking and extensive change since 1963-64 was the more extensive area of the hard-compacted, mudcracked surface throughout the northern part of the playa. This change may relate in part to the heavy flooding of the playa in November and December of 1967; a conclusion that is based upon changes in the hard-compact mudcracked surface observed from Jaunary to February and discussed later in the report. Part of this change could also result from long-term changes in the surface of Troy Playa. Other differences of the playa surface in 1968 not present in 1963 included a smooth hard surface underlain by white calcareous and evaporite material, xerophytes and xerophyte mounds encroaching onto the playa on the eastern margin, and the death and decay of some of the vegetation mounds in the southeastern part of the playa.

The area of hard, white calcareous material was probably deposited as a result of continuous playa floodings, and was harder and more compact than the adjacent brown puffy surface because of compaction by standing water. The white surface had a microrelief ranging from 0 to about 1/4 inch. Some new polygons had begun to develop on this surface whose average diameter ranged from about 4 inches to 1 foot. There was a faint suggestion of an earlier set of polygons whose average diameter ranged from about 1-1/2 to 3 inches; however, this set had been almost destroyed by the floodings in 1967. The surface crust of calcium carbonate and other evaporites gave the surface its

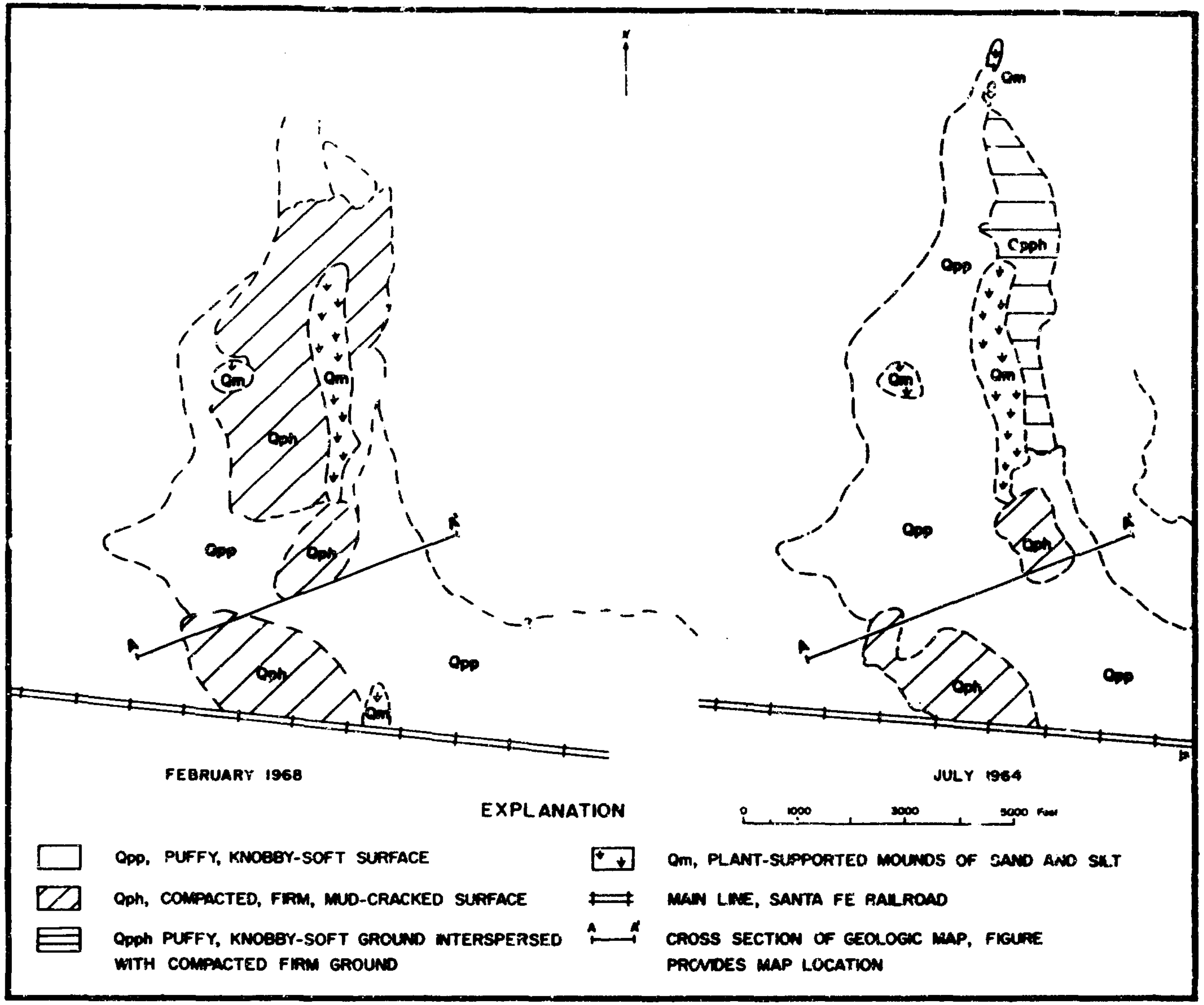


Figure 14. Changes in the surface of Troy Playa from 1964 (mapped by Charles Groat) to 1968 (mapped by Ward S. Motts).

light cream to white color. As the result of the playa floodings, evaporites from the surface crust were taken into solution and deposited in the white, calcareous area. Groat (1967, p. 86; this report, Fig. 13) made a similar observation in 1964.

In places this smooth white surface had been recently uplifted by capillary deposition, as shown by separation and heaving of polygonal cracks. Some of the polygons in these areas averaged 1 to 1-1/2 inches in diameter and they were separated by cracks ranging from about 1/16 to 1/8 inch, however, the 1/8 inch size seemed to be the most common. In another part of the surface the playa was characterized by a wavy surface in which small, gentle rises about 1-1/2 inches across were separated by depressions of the same size. The smaller rises are cores of former polygons that escaped destruction from the November flooding of the playa.

Areas of decaying and dead vegetation indicated expansion in some areas of the south part of the playa; however, other parts of Troy Playa were also being encroached by large areas of xerophytes and vegetation. The xerophytes developed on mounds that ranged from about 1/3 foot to 1-1/2 feet high. If these plants and mounds took only 4 to 5 years to establish themselves as the data indicates, it would show that the new environmental conditions were rapidly established on the playa surface. A small area of vegetation not present when Groat mapped the area was along the Santa Fe Railroad near the middle of the playa. Playas such as Troy underlain predominantly by silt and sand may be characterized by migration of vegetation types and xerophytes. This process of vegetation migration would help explain why sand-silt playas have relatively high permeability and transmissibility. The vegetation roots open up and increase the permeability of the playa sediments which in turn allows freer and more ready transfer of water by capillarity from the ground-water table to the surface of the playa.

GROUND WATER IN THE TROY PLAYA AREA

General Conditions

Most ground water in the Lower Mojave Valley occurs in alluvium of the fans and valley fill. Small amounts occur in localized fault zones in the bordering mountains. Ground water is unconfined in the western and central parts of the Valley where the alluvium is chiefly sand and gravel. Confined ground water occurs in the playa area at the eastern end of the Valley because of an increase in the thickness and lateral extent of clay beds. The depth to water varies from 7 feet at Troy Playa to 40 to 50 feet in the vicinity of Mountain View Road in the western part of the study area. In some places near the playa, ground water is confined more than 100 feet beneath the surface by thick clays.

The dominant direction of ground-water movement is from west to east along the basin with minor flow toward the basin from the alluvial fans bordering the basin on the south (Groat, 1967, Pl. 3). Part of the water moves toward the Mojave River near the northwest corner of the Cady Mountains, whereas some flows toward Troy Playa.

Recharge

Ground-water recharge to the Lower Mojave Valley and Troy Playa area occurs in three ways: (1) as subsurface inflow from the west through the channel sands of the Mojave River, (2) as direct recharge through the channel sand of the Mojave when the river is flowing, and (3) from rainfall over the Newberry Mountains where rain water percolates to the ground-water reservoir through alluvial-fan sediments.

The Mojave River originates in the San Bernardino Mountains to the southwest and crosses several basins along its course, including the one in which Troy Playa is located. Surface flow reaches the Lower Mojave Valley only on rare occasions of severe storms, prolonged rainfall, or heavy snow melt. Subsurface inflow from the west, however, is considered the chief source of ground-water recharge to the basins crossed by the Mojave River (Bureau of Reclamation, 1952, p. 14). Estimates are not available for each of the basins, but the California Department of Water Resources (Valentine, 1963) estimated that 70,500 acre-feet of water per year enters the subsurface a few miles downstream from the headwaters area.

The contour map of the potentiometric surface in the alluvium east of the Newberry Fault, which trends northwest across the Lower Mojave Valley fan near Newberry (Groat, 1967, Pl. 3), demonstrates that the potentiometric surface in this part of the Valley is at a higher elevation than the river, hence the river drains rather than recharges the ground-water reservoir. This condition does not necessarily negate recharge along the entire Mojave River, for recharge may occur at the west end of the Valley near Barstow, where the river enters the Valley from a narrow canyon. The inflow could reach the basin-fill alluvium in this area, flow east, and eventually rejoin the water in the channel sands near the east end of the basin. Thus ground water impounded behind the Newberry Fault and at a higher head on the west side, recharges the eastern part of the basin, and much of the water behind the fault could come from inflow along the Mojave River. The problem of recharge by the Mojave is a complex one and other aspects will be discussed in the section on water quality.

Infrequent surface flow along the Mojave furnishes some recharge to the ground-water reservoir, for the channel sands are very permeable. As is true

for subsurface inflow, recharge from surface flow must occur west of the Newberry Fault where head relationships are favorable. The amount of recharge would depend on the duration of flow during flooding and on the frequency of flooding or flow. No attempt was made to estimate these, and it can only be hypothesized that the total amount is small, for flooding is infrequent.

The average annual precipitation in the region is approximately 3 inches. Rainfall usually occurs as thunderstorms, generally over the Newberry Mountains which border the basin on the south. Much of the rainfall runs off, collects in pools at the toes of the alluvial fans, and evaporates. Some undoubtedly percolates into the alluvium and reaches the ground-water reservoir in the basin, but this amount must be small. The absence of ground water in the basin east of the Pisgah Fault indicates that rainfall alone is not an important source of recharge.

Recharge by precipitation and surface flow of the Mojave River must be negligible under the present arid regime. Subsurface inflow from basins above the Lower Mojave Valley, by means of the channel sands, must be considered, but the amount and significance of this are open to serious debate. It is most probable that most of the subsurface water in the basin is a relic from a previous, more humid climate; perhaps the last Pleistocene pluvial. The Mojave was probably a perennial stream during much of that time, for it maintained a large lake, Lake Manix. Recharge under these conditions would have been appreciable, whereas under the present arid regime it is not.

Discharge at Troy Playa

Ground water discharges from the Lower Mojave Valley in four ways: (1) as a result of man's pumping for domestic, agricultural, industrial, and recreational use; (2) as outflow over and through the channel sands of the Mojave River at Afton Canyon; (3) by evapotranspiration from crops and from phreatophytes concentrated along the Mojave channel; and (4) by evaporation of capillary water at Troy Playa. The reader is referred to Groat (1967, p. 117-119) for more information on the first three methods of discharge.

Discharge of ground water from the capillary fringe on Troy Playa has produced the puffy or self-rising surface that dominates at Troy Playa. The puffy ground of Troy is not as well developed as the surfaces of Bristol, Searles, or Danby Playas, possibly because the zone of saturation is deeper beneath the surface at Troy, thus the intensity of discharge is less.

There is ample evidence from water-level records (Dyer and others, 1963) that ground-water levels have been lowering throughout the Lower Mojave Valley during the past 25 years. This lowering has undoubtedly decreased the discharge of ground water from Troy Playa. Discharge is presently occurring in some areas, as the following evidence indicates. A light rain during August 1963 promoted flow in the channels crossing the central playa. Upon desiccation, the muds in the channel bottoms developed mudcracks, destroying the puffy or self-rising structure. Examination of the same areas in July 1964 showed that the puffy ground had renewed itself at the expense of the mudcracks, demonstrating that discharge from the capillary fringe was still occuring. The amount of discharge is not known, but is probably much decreased from previous periods of higher water-table conditions.

Quality of Water

Ground water pumped from Troy Playa and vicinity is generally too mineralized for consumption or irrigation. West and north of the playa, however, the water is of much better quality and quality increases westward (Groat, 1967, Pl. 4). Total dissolved solids (TDS) in the ground water of the Lower Mojave Valley east of the Newberry Fault range from a low of 230 parts per million (ppm) in the west to greater than 5,600 ppm at Troy Playa. Cl^-, SO_4^{--}, and HCO_3^- are the most abundant anions while Na^+ and Ca^{++} are the most numerous cations. Fluoride and boron are also present; fluoride exceeds the drinking water standards of the Public Health Service (1962) in isolated areas, and the high boron content causes some problems for irrigation north of the study area. In the better water-quality zones, HCO_3^- exceeds Cl^- plus SO_4^{--}, but in the highly mineralized waters in and around Troy Playa, Cl^- plus SO_4^{--} exceeds HCO_3^-.

The quality of ground water in the eastern part of the Lower Mojave Valley varies in two directions: vertically and laterally. Shallow wells, to depths of 15 to 35 feet, throughout the area generally yield water of sufficiently poor quality to render it unusable. This water, yielded by shallow aquifers, probably originates as recharge from runoff and as drainage from irrigation excesses. The mineralization is a result of leaching of the surficial sediments of the alluvium. Some of the shallow water may be perched and not flushed out by circulation.

Deeper waters are commonly of better quality. At several locations, shallow wells (50 to 100 feet) are located within 100 yards of deeper (100 to 200 feet) wells, and the deeper wells, in each instance, yield water of better quality. A well drilled in sec. 21, T. 9 N., R. 4 E. in 1963 provides

a good example of vertical zonation of water quality. The well was cased and the screens set at approximately 200 feet. After two weeks of nearly continuous pumping, the water was tested and found to contain 2,100 ppm TDS. In 1964, after the screens had been raised 80 to 100 feet, the TDS was 4,200 ppm. At another location, sec. 26, T 9 N., R. 3 E., water from an 80-foot well contained 3,500 ppm TDS while a nearby 256-foot well yielded water containing 1,526 ppm TDS. Other examples could be cited, but these illustrate the point. The very shallow aquifers yield water of very poor quality and, to an unknown limit, the deepest aquifers yield the best water.

Ground water changes from less than 300 ppm TDS in the vicinity of the Newberry Fault and the Mojave River, to more than 1,000 ppm TDS at and surrounding Troy Playa (Groat, 1967, Pl. 4). The change from 500 ppm to 1,000 ppm is relatively abrupt with no consistent pattern, suggesting that the 1,000 ppm contour may reflect an interface between comparatively distinct waters. In general, the increasing mineralization of ground water corresponds to increasing thickness and lateral extent of brown clays and silty clays toward the playa.

The relation of the configuration of the potentiometric surface to water quality is interesting and significant. West of Newberry Fault, where the potentiometric head is higher than east of the fault, ground water contains less than 300 ppm TDS. The same is true immediately east of the fault where the influence of the higher head west of the fault is clear (Groat, 1967, Pl. 4). The better-quality water east of the fault and south of the Mojave River channel corresponds to areas of highest head. The poorer-quality water projecting westward from Troy Playa corresponds to areas of lower head or troughs in the potentiometric surface. These troughs are

related to areas of high pumpage where irrigated farming is extensive. Large withdrawals have lowered the head of the better-quality water below the head of the poorer-quality water of the playa area, allowing the more mineralized water to intrude into the aquifers. The areas of intermediate quality probably represent zones of mixing of the two waters where the head differences are not great. The northern portion of the Troy Playa area is influenced by the higher head of the better-quality water, and highly mineralized water has not entered aquifers there.

Thus water of good quality (less than 300 ppm TDS) from west of the Newberry Fault flows through the fault plane into the area east of the fault; the head of the better-quality water east of the fault is related to the head west of the fault. The poorer-quality water (greater than 1,000 ppm TDS) of the Troy Playa area is at a lower head and extends westward into fresher-water aquifers only where the head of the fresher water has been lowered, by pumping, below the head of the poorer-quality water.

Continued heavy pumping and future development of the better-quality water will result in further westward extension of water of poor quality. Comparisons of quality-of-water data I collected in 1963 and 1964 with data reported by Dyer and others (1963) for 1956 to 1959, indicate that deterioration of water quality has occurred; the area influenced by the poorer-quality ground water has expanded westward. The future of this portion of the Lower Mojave Valley may depend more on the rate and extent of encroachment of mineralized water than on the amount of water in storage.

SUMMARY AND CONCLUSIONS

The sediments that underlie Troy Playa were deposited in part in Lake Manix of late Pleistocene age and in part in more recent ephemeral playa lakes. Two facies, an upper mud facies and an underlying sand facies, are recognized in the upper playa sediments. The texture and geometry of these sediments and the potentiometric surface of the shallow ground water are controlling factors in the development of the surface characteristics of the playa.

Troy Playa exhibits a puffy surface where the potentiometric surface of ground water in the shallow aquifers is within the fine-grained mud facies, and capillary rise of ground water is pronounced. A hard-compacted playa surface is present in the southwestern part of the playa where the potentiometric surface is within the sand facies. The presence of sand above the saturated zone inhibits capillary rise and permits the development of a hard-compacted playa surface from flooding followed by desiccation.

The effects of rainfall and localized flooding on the playa surface in 1963 and 1964 noted by Groat, and larger-scale surface changes mapped by Motts during the winter of 1967-68, clearly indicate that the surface features of a ground-water discharging playa are not stable. Changes of morphology on the playa surface are relatively rapid in response to temporary flooding of the playa. Flooding and subsequent desiccation converts puffy ground to hard-compacted ground; however, capillary discharge of ground water soon converts this hard-compacted surface back to the puffy type. Changes in the extent of the playa and in vegetation patterns since 1964 were noted by Motts in 1967-68; plants and plant mounds occupied areas of the playa in 1967-68 that they did not occupy in 1964. Expansion of the

flat playa surface had occurred in areas where dying plants were no longer able to support sediment mounds.

Stratigraphic and geomorphic relationships of playa, desert-flat, alluvial-fan, and eolian sediments suggest other changes in the extent of Troy Playa and related features during late Pleistocene and Recent time. The study and understanding of modern, short-term changes in these relationships, and of the processes that cause them, has provided the framework for the interpretation of these past changes and their causes.

The poorest-quality ground water in the Lower Mojave Valley occurs at shallow depths and in and around Troy Playa where clay beds are thickest and most numerous. Ground water of good quality is present west of Troy Playa. The head of this good-quality water is being lowered below that of the poor-quality water of the playa area by heavy pumping, and the poor-quality water is intruding westward into previously fresh-water aquifers. The continued lowering of the potentiometric surface in the Lower Mojave Valley will probably affect the future morphology of the Troy Playa surface. The decline in the potentiometric surface will result in conversion to a hard-compacted surface as the effects of capillary discharge become negligible and desiccation prevails.

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CHAPTER 6: RECONNAISSANCE GEOLOGY OF CLAYTON PLAYA, NEVADA

Ward S. Motts

David B. Matz[1]

ABSTRACT

Clayton Valley is the terminal discharging locality for deep water circulation throughout the Tonopah area of Nevada. Deposition of salts accompanying ground-water discharge is a significant factor in the morphology and genesis of playa surface types. The following eight major geomorphic types have been recognized in the Clayton Playa area: (1) a Plant-Mound Zone where abundant mounds, 1 to 4 feet high, are capped by pickleweed and other plants; (2) a Channeled-Puffy Zone characterized by numerous streams and channels that dissect the otherwise smooth surface to depths up to 2 feet; (3) a hard indurated crust of calcium carbonate (Travertine-Crust Zone) characterized by crust commonly ranging in thickness from 1/2 to 1 inch; (4) a Calcareous-Subsurface Zone characterized by many thin, shallow, calcareous beds interbedded with sand and silt; (5) a Travertine-Butte Zone characterized by buttes capped by bedded calcium carbonate. The buttes, probably part of an old playa surface, owe their elevated position either to tectonic movements or to erosion of the surrounding surface; (6) a Central-Playa Zone underlain predominantly by silt, has a wet smooth surface and is underlain by a shallow water table less than 4 feet deep; (7) irregular knobby areas caused by the encrustation of salt and deposition of silt and mud around accumulations of twigs, branches and roots carried into the playa by floods (Knobby-Hard Zone) or around pickleweed and other roots (Knobby-Soft Zones); (8) a Mine-Tailings Zone consisting of stratified tailings of fine sand or silt and clay 1 to 10 feet in thickness. The deposits of the tailings are well bedded outside the playa boundary; however, they lose their stratification and become disrupted, soft and puffy within the playa where capillary discharge occurs.

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[1]Geologist, Shell Oil Company, Midland, Texas.

INTRODUCTION

Clayton Playa occupies the lowest part of Clayton Valley, a large topographic depression in Esmeralda County, Nevada. Clayton Valley lies south of Big Smoky Valley, between the 117th and 118th meridians, and south of the 38th parallel (Chap. 1, Fig. 5). Silver Peak, the only settlement in the valley, is the headquarters for the Foote Mineral Company which extracts lithium from highly saline ground water underlying Clayton Playa. Mendenhall (1909) made one of the earliest hydrologic studies of Clayton Valley by describing some of its wells and springs. Dole (1912) discussed the economic potential of the valley's salt deposits; Phalen (1919) further described the salt deposits. Meinzer (1917) described the geology of Clayton Valley and Rush (1968) discussed its hydrogeology in relation to a larger area of desert valleys.

Clayton Playa, Big Smoky Playa, Columbus Salt Marsh, Fish Lake Valley, Mud Lake, and Clayton Playa East form a diversified playa complex in the area of Tonopah, Nevada. Clayton Playa East and Mud Lake occur at the lowest topographic elevations of Alkali Springs Valley and Ralston Valley, respectively. Clayton Playa and Columbus Salt Marsh are playas underlain by sand, silt, and evaporites, whereas the other playas in the complex are underlain by fine-grained silt and clay. Clayton Playa lies at an altitude between 4,200 and 4,300 feet; Columbus Salt Marsh, between 4,500 and 4,600 feet; Big Smoky Playa (near Blair Junction), between 4,700 and 4,800 feet; Clayton Playa East, between 4,900 and 5,000 feet; and Mud Lake, at about 5,200 feet. Field observations indicate that the amount of ground-water discharge is related to the elevation of the playas. Clayton Playa and Columbus Salt Marsh, at the lowest elevations, discharge the largest amount of ground

water; Big Smoky Playa, at an intermediate elevation, discharges a moderate amount; and Mud Lake, at the highest elevation, discharges the least amount of ground water. Clayton Playa, the lowest in elevation, appears to be the "terminal" discharging area for water circulating through deeper aquifers of Ralston Valley, Alkali Springs Valley, Big Smoky Valley and Fish Lake Valley, a conclusion also reached by Rush (1968, p. 15). The above information indicates that the "basement" rocks underlying the Tonopah Playa Complex are permeable enough to allow interbasin water circulation, a condition also present in southwestern Nevada near Mercury, Nevada (Winograd 1962, p. c108-c111).

The bedrock geology of the Clayton Valley is described in some detail by Albers and Stewart (1965). The bedrock surrounding the valley consists primarily of volcanics, including rhyolite, and of ash flows, tuff, and andesite. Minor amounts of Tertiary basalt are found in areas surrounding the playa. Part of the higher mountains are underlain by the Pogonip group which consists primarily of thin bedded limestone interbedded with shale. Rush (1968, p. 10) suggests that the percentage of carbonate rocks may increase with depth, which in turn increases the solution openings and the subsurface permeability.

Unconsolidated and semi-consolidated alluvium resting on bedrock consist of Older Alluvium of Pliocene and Pleistocene age and Younger Alluvium of late Pleistocene and Recent age (Albers and Stewart, 1965). The Older Alluvium is more highly consolidated and generally has lower permeability than Younger Alluvium which forms the principal aquifers for valleys of the Tonopah Complex. The lake and playa deposits belong to Younger Alluvium.

The relatively flat playa surface is bounded on all sides by the desert flat, which gradually rises to the adjacent mountains from the playa surface. The desert flat is underlain predominantly by silt, sand, granules, and fine gravel. Some areas of the desert flat have a soft knobby or puffy surface which may be due to the capillary action of ground water. The desert flat is underlain by thick bajada deposits and by thin pediment deposits. Streams flowing in alluvial fans have supplied much of the detrital material to Clayton Valley.

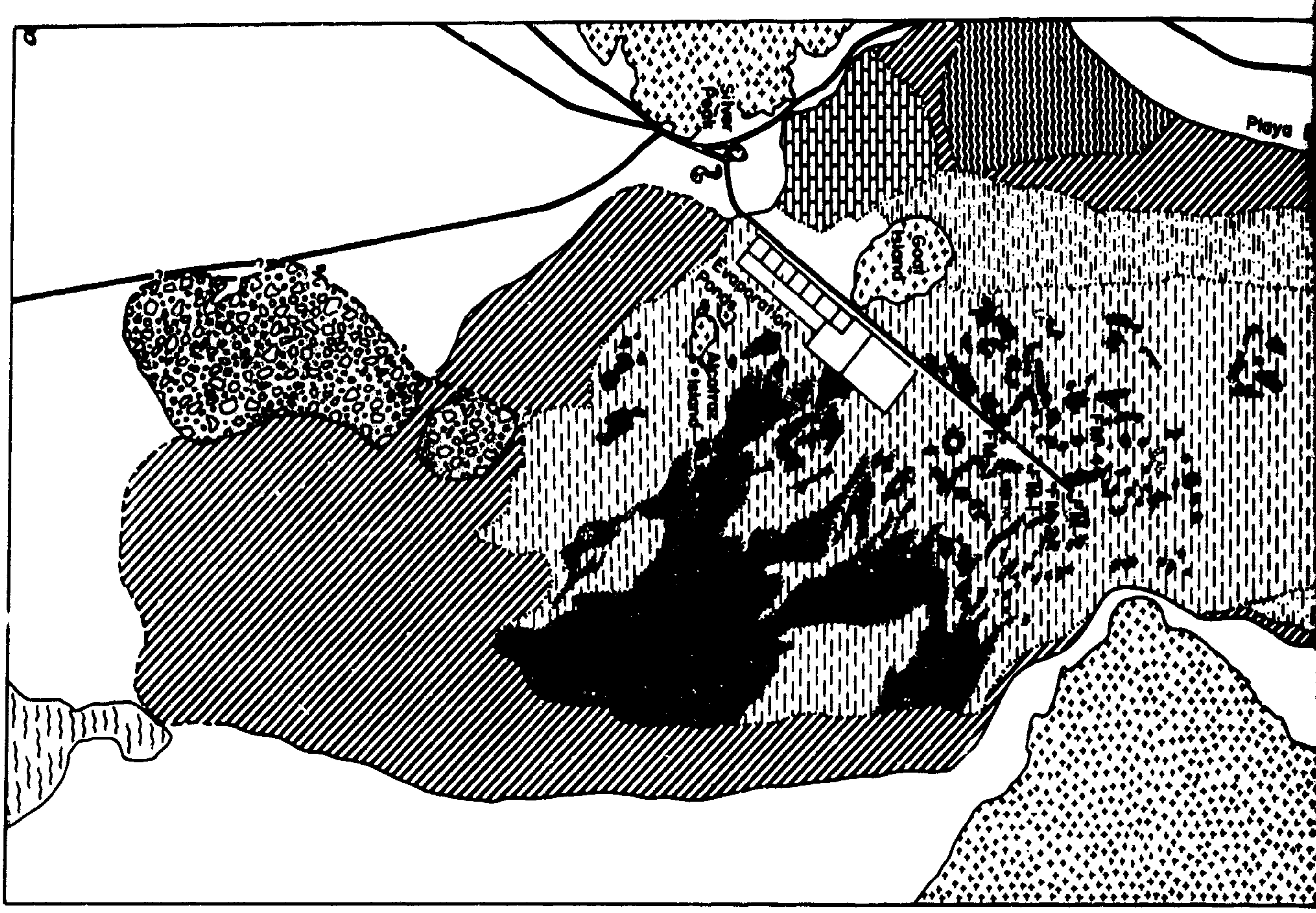
PLAYA SURFACE FEATURES

This chapter on the geology of Clayton Playa is based on field work by David Matz during the summer of 1965 and by Ward Motts intermittently from 1963 to 1968. The authors are grateful to Foote Mineral Company for their cooperation which made this study possible.

Clayton Playa, typical of some other ground-water discharging playas, is characterized by a diversity of playa types (Fig. 1). The central part of the playa is barren because high mineralization of the ground water prevents vegetation growth. Vegetation, chiefly greasewood, is abundant on the desert flats adjacent to the playa where the ground water is less highly mineralized; salt grass and pickleweed become more abundant toward the playa where water is more highly mineralized. The playa surface can be subdivided into six distinct geomorphic areas or zones: the Plant-Mound Zone, the Channeled-Puffy Zone, the Travertine-Crust Zone, the Travertine-Buttes Zone, the Calcareous-Subsurface Zone, the Central-Playa Zone, and the Mine-Tailings Zone.

Abundant plant mounds form the well-defined Plant-Mound Zone in the eastern, southern, and western parts of Clayton Playa (Fig. 2). Pickleweed is the predominant plant type of this zone. The plants cap small mounds, 1 to 4 feet high, which are underlain by medium-sized, well-sorted sands of probable aeolian origin. The mounds appear as "islands" because they are commonly separated and surrounded by salt-encrusted puffy ground characterized by sediments of coarse silt to fine sand. Toward the center of the playa the Plant-Mound Zone grades into the Channeled-Puffy Zone.

The Channeled-Puffy Zone on the northeastern and western parts of the playa derives its name from the numerous streams and channels that dissect,



EXPLANATION

- Salt-Encrusted areas of knobby-soft ground and salt encrusted areas of knobby-hard ground.
- Hard indurated crust of calcium carbonate, (Travertine-crust zone).
- Zone of abundant vegetation mostly pickleweed, growing on small mounds. Knobby-soft, salt-encrusted ground separates the mounds, (Plant-mound zone).
- Knobby-soft, salt-encrusted surface, numerous channels, few vegetation mounds, (Channelled-puffy zone).
- Silt and sand underlain at shallow depth by thin beds of carbonates which thicken with depth. Generally thin salt efflorescence on surface, (Calcareous-subsurface zone).
- Smooth moist surface, predominantly silt, salt efflorescence when dry, (Central-Playa zone).
- Tailings of predominantly silt and fine sand, (Mine tailing zone).

- Old
- Bu… car…
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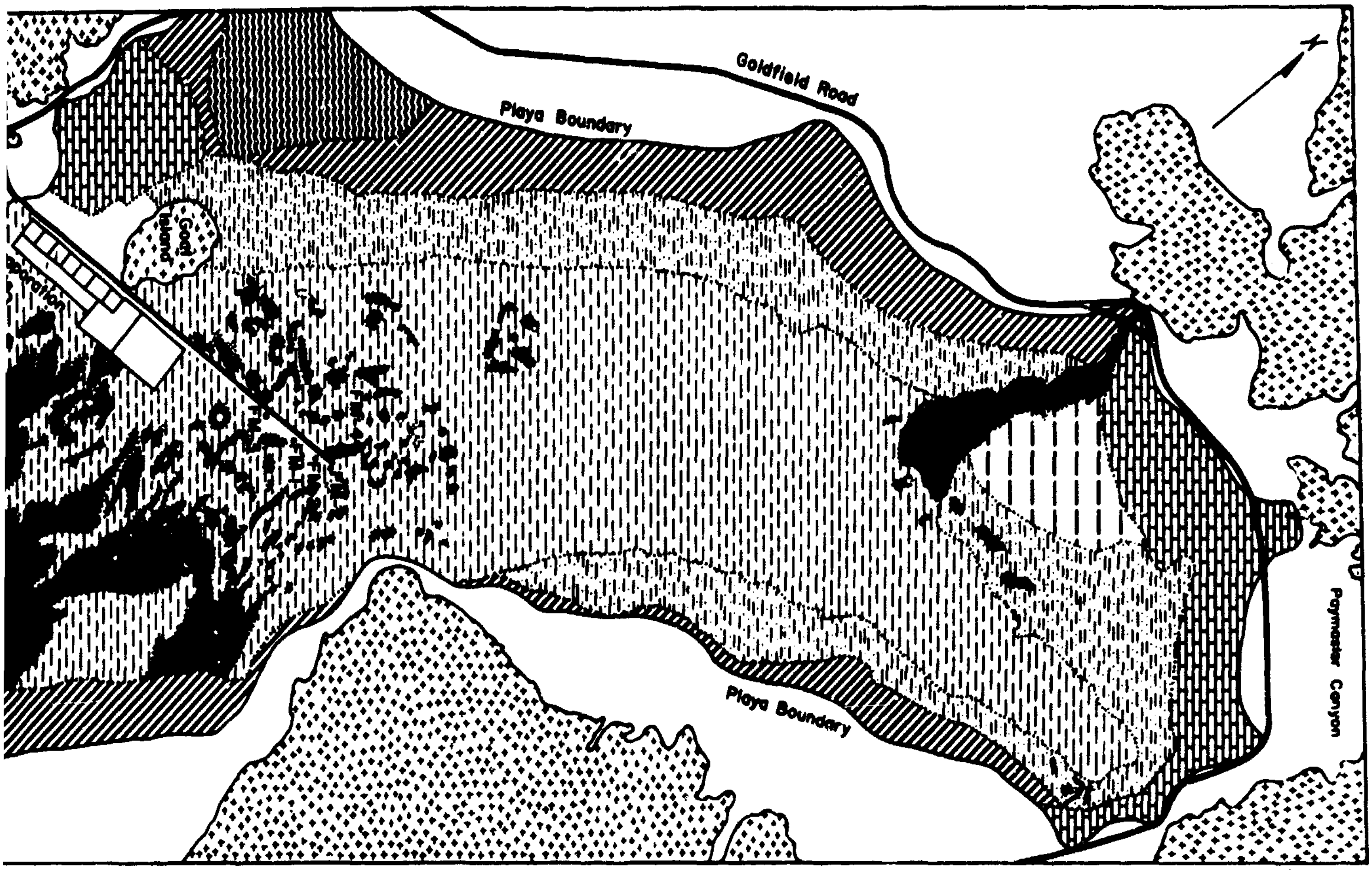
Figure 1. Geology of Clayton Playa and adjacent areas.

A



EXPLANATION

round and salt encrusted

ite, (Travertine-crust zone).

leweed, growing on small
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rous channels, few vegetation

by thin beds of carbonates
salt efflorescence on

salt efflorescence when dry,

and, (Mine tailing zone).

reas.

Older alluvium, heavily varnished.

Buttes 6-8 feet high capped by bedded calcium carbonate, (Travertine-buttes zone).

Alluvium and colluvium of the desert flat.

Bedrock.

Area of sand dunes.

---- Playa boundary, dashed where gradational.

— — Possiable fault.

.... Surface zone-contact.

FM 4 Well

SCALE

1 ½ 0 1 2 miles

Mapped by David Matz, 1965

β

Figure 2. Small hills capped with pickleweed (Plant-Mound Zone). Note puffy ground between hills.

Figure 3. A channel with ripple marks in the Channeled-Puffy Zone (northeastern part of the playa); current direction toward center of playa indicated by arrow.

to depths up to 2 feet, the otherwise smooth surface of the playa. The channels, commonly containing ripple marks, are the result of a slight change in slope from the outer to the central part of the playa (Fig. 3). A pronounced Channeled-Puffy Zone does not occur in the southern part of the playa where the gradient toward the central portions is less steep. Few plant mounds are present on the channeled surface, which is probably underlain by highly mineralized ground water. Pickleweed cannot survive if ground water has a total dissolved solid content greater than 5%. Silts and clays of this zone are wet indicating the surface is close to the zone of saturation. A moderately hard crust containing salts and carbonate is underlain by fine-grained sands and silts with a granular texture. Puffy ground of this zone has a relief of about 1 inch.

A hard indurated crust of calcium carbonate (Travertine-Crust Zone) occurs in the northern and western part of the playa near Silver Peak (Figs. 1 and 4). The crust commonly ranges from 1/2 to 1 inch; however, any area which had a trace of a crust was mapped as belonging to this zone. The surface of this zone, which is hard and smooth enough to support aircraft runways in the western part of the playa, becomes poorly defined in the area along the Goldfield Road (Fig. 1). The travertine crust of this zone may have been deposited by shallow ground water flowing over and intermixing with more highly mineralized brine near the playa center.

In the northern part of the playa, beds of calcium carbonate in the subsurface form the Calcareous-Subsurface Zone which merges with the Travertine-Crust Zone (Fig. 1). The surface of the former zone is generally underlain by a thin coating of white salt. Many thin shallow calcareous beds characteristic of the Calcareous-Subsurface Zone are interbedded with sand and silt

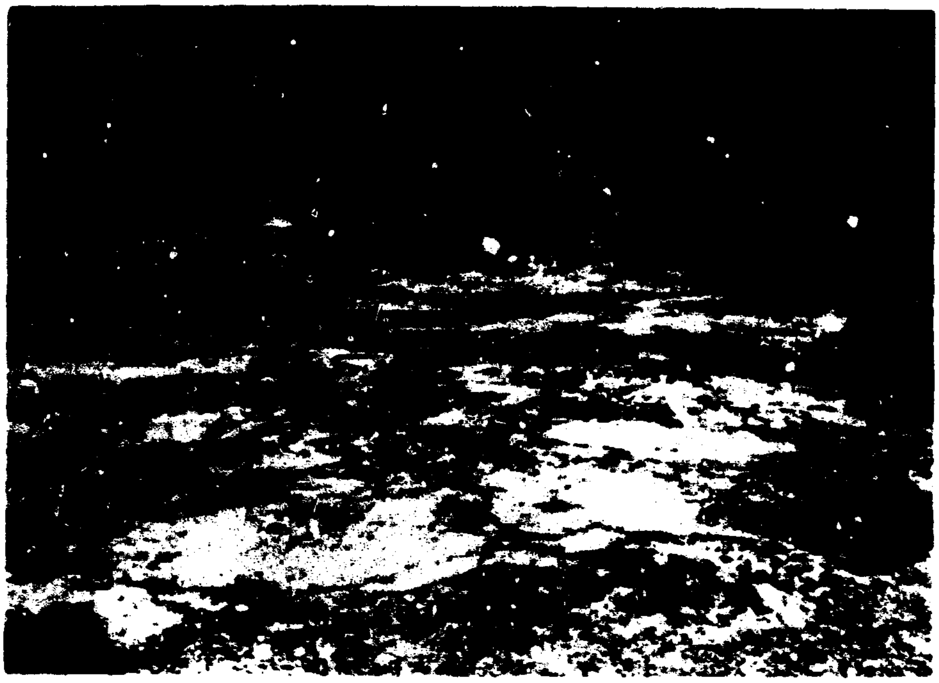


Figure 4. Travertine-Crust Zone in northern part of playa.

Figure 5. A typical butte of the Travertine-Butte Zone in the southern part of the playa. Note darker hue of butte surface due to desert varnish.

and occur at depths as shallow as 6 inches. The depths vary considerably from the surface to the carbonate beds which become thicker and occur at shallower depths in a northward direction.

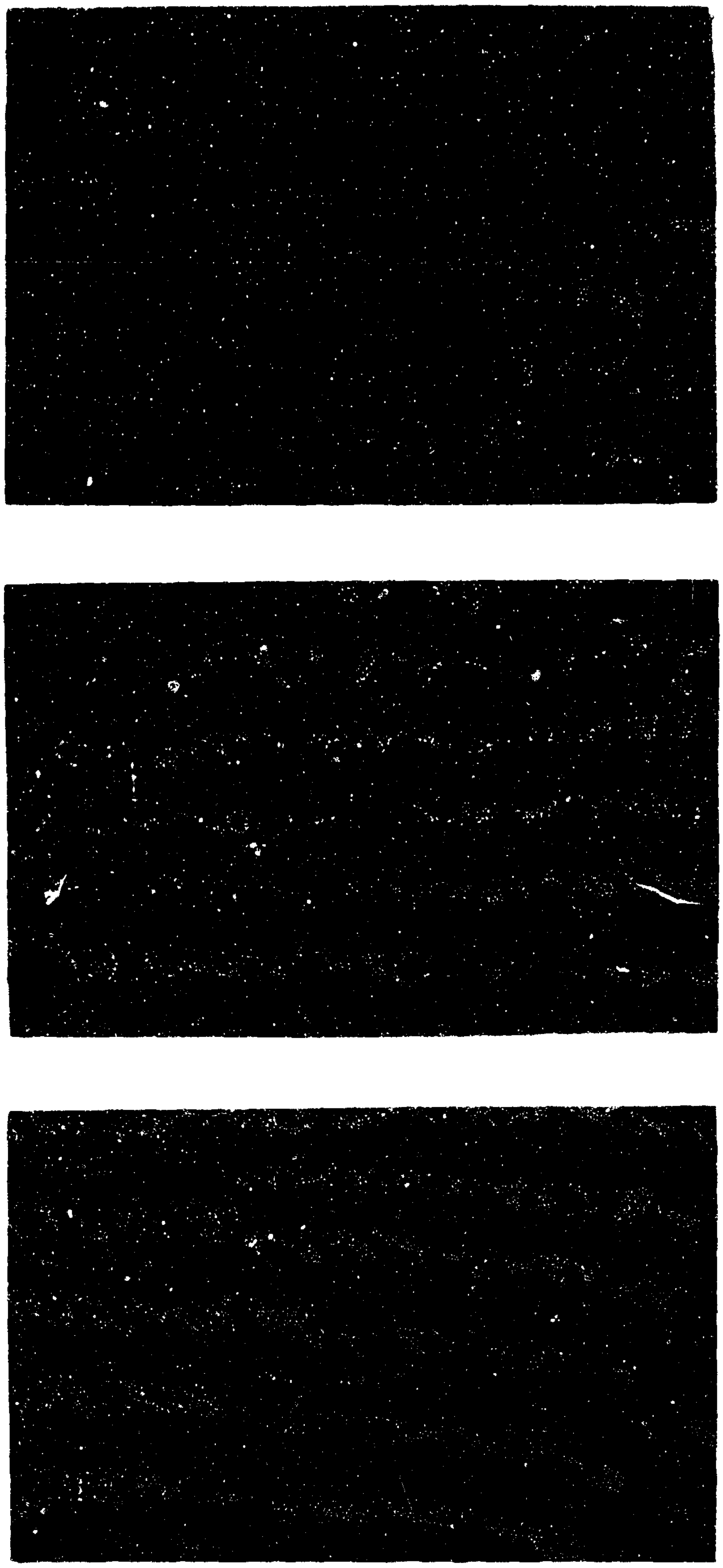
Buttes capped by bedded calcium carbonate form the Travertine-Butte Zone which occurs only in the southern part of the playa. The buttes were probably originally part of an older playa surface--perhaps a Travertine-Crust Zone or a Calcareous-Subsurface Zone. The buttes, 6 to 8 feet high, have the dark gray to black surface of desert varnish (Fig. 5). The beds of calcium carbonate have a crude bedding, which ranges in thickness from 1/2 foot to 4 feet. Numerous pisolites indicate that the travertine buttes may have been originally spring deposits or may have formed in shallow playa lakes. The turbulence of discharging spring water or of playa-lake water would favor pisolite formation. The surface of the buttes in many places is covered with fragments of calcium carbonate ranging in size from a fraction of an inch to 3 to 4 feet along their longest dimension. Many of the fragments are highly etched from solution by rainwater or sheetwash. Some younger travertine buttes with a light gray surface of desert varnish occur at lower topographic levels than the higher buttes discussed above. These younger buttes (not mapped on Fig. 1) are probably of the same origin as the higher ones; i.e., part of older playa surfaces which occur at higher elevations either because they have been raised by tectonic movements or because the surrounding surface has been lowered by erosion.

The central part of the playa, herein called the Central-Playa Zone, is underlain predominantly by silt, has a wet smooth surface, and is capped by a thin crust of salt. On aerial photographs the zone appears as gradational shades of dark and light grays caused by varying thickness of the salt crust. The lighter shades are caused by thicker salt crusts, whereas

the absence or thinning of salt produces a darker shade. The ground-water table along the outer margins of the Central-Playa Zone ranges between 2 and 4 feet below the surface, and it appears to become shallower toward the center of the playa where the water table and topographic surface occur at almost the same level (Fig. 6A). Numerous and diverse textural features occur in the Central-Playa Zone, including elliptical and circular areas of salt, ranging from about 1/2 foot to 2 feet in diameter (Fig. 6B). Numerous small sink holes and closed depressions may be zones of higher transmissibility, where rising water under hydrostatic head has caused collapse of the surficial playa sediments (Fig. 6C).

Small isolated areas and large areas of highly irregular ground occur in the central and southern part of the playa. They are called in this report "knobby-hard" ground if they are hard and coherent, and "knobby-soft" ground if they are soft, friable and easily deformed with slight pressure. Both types of ground are surficial features and grade within a few inches below the playa surface into moist silt and sand. The "knobby-soft" ground resembles puffy ground, but the former has a microrelief of from about 1/2 to 4 inches, whereas the latter has a microrelief of only about 1/2 to 1-1/2 inches. The knobby-hard ground has a microrelief ranging from about 1 to 9 inches. Puffy ground was formed by capillary discharge and deposition of salts in the surficial playa silts, whereas the knobby-soft and knobby-hard ground were formed around vegetation in the manner described in the following paragraph.

Knobby-hard ground occurring near the center of the playa is formed around the accumulation of twigs, branches, and roots carried into the playa by floods. Salt crystallizes in the wood which soon becomes saturated with brine, while at the same time surface waters transport and deposit mud



A

B

C

Figure 6. Central-Playa Zone. A. Soft smooth surface where the water table and the topographic surface nearly coincide. B. Elliptical and circular areas of salt. C. Sink hole at boundary between Channeled-Puffy Zone and Central-Playa Zone.

and silt which becomes trapped in the network. The continued crystallization of salt and deposition of mud and silt eventually completely transforms the original skeleton of wood into knobby-hard ground (Fig. 7). The above theory is substantiated by the fact that small decayed fragments of wood occur in some of the areas of knobby-hard ground. The high mineralization near the playa center probably accelerates the above process.

Many areas of the knobby-soft ground away from the central part of the playa form from the encrusting of salt around the roots of pickleweed and other plants. The above theory is substantiated by the fact that one can observe a complete gradation of (1) knobby-soft ground associated with living pickleweed through (2) knobby-soft ground interspersed with dead pickleweed roots to (3) areas underlain solely by knobby-soft ground (Fig. 8). In the southern part of the playa, a large expanse of knobby-soft ground appears to originally have been a pickleweed area where the plants may have been killed by an increase of ground-water salinity (Fig. 9). This is probably another example of the expansion of playas at the expense of the desert flat.

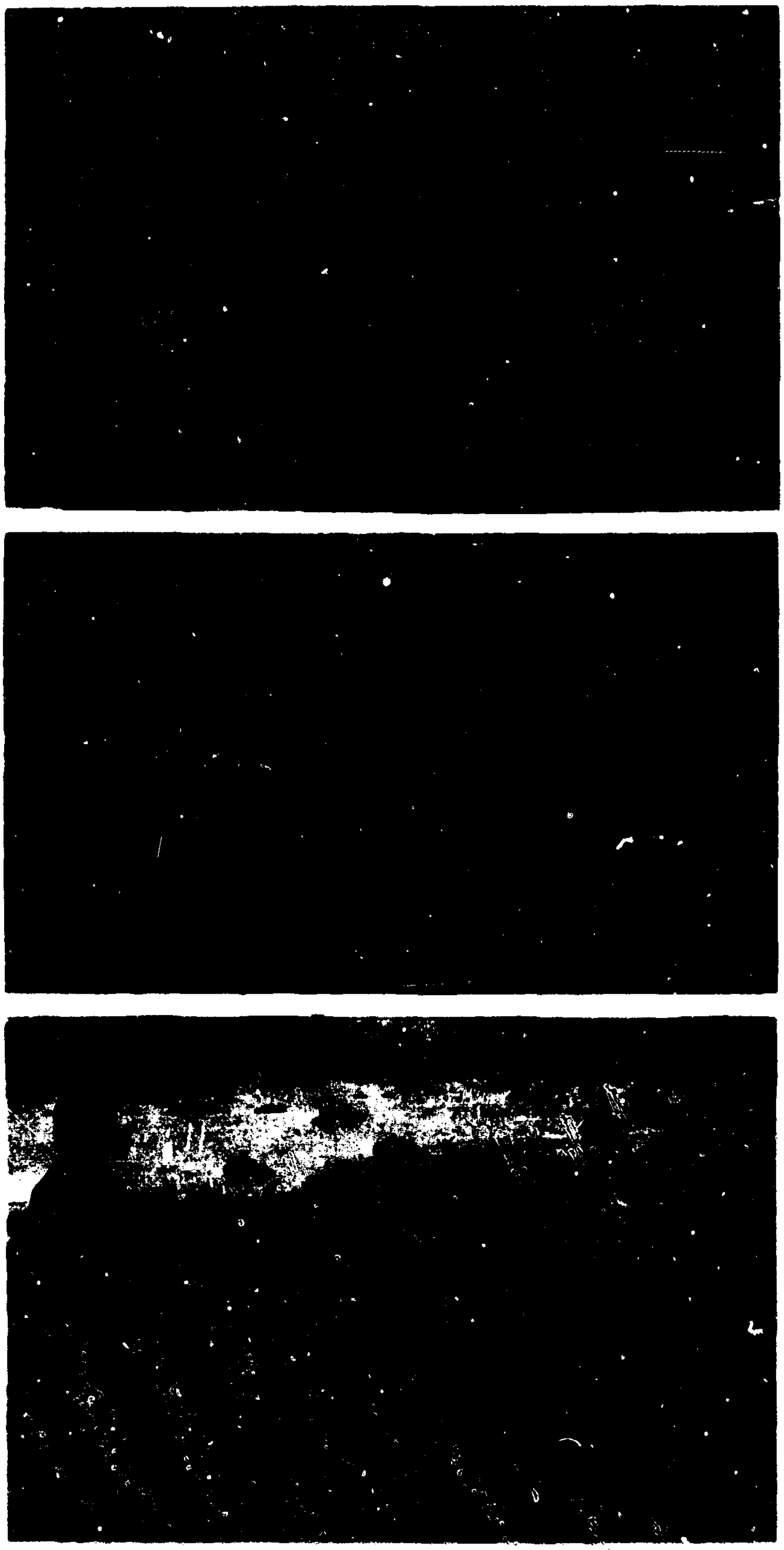
The Mine-Tailings Zone occurs in the vicinity of the junction of Goldfield Road and Route 47 (Fig. 1) where tailings have been washed onto the playa from the former mining settlement of Blair. These deposits consist of fine sand, silt, and clay which are finely bedded and range up to ten feet in thickness (Fig. 10). In one area, the deposits have been highly dissected by intermittent streams resulting in a badland type of topography. Although deposits of the Mine-Tailing Zone were formed only from [illegible] to 70 years ago, they have now been almost completely dissected by surface streams. The deposits of tailings are well stratified outside the playa boundary;

A

B

C

Figure 7. Stages in the development of knobby-hard ground. A. Accumulation of wood on the playa surface as the result of flooding. B. A more advanced stage than A--salt is crystallizing in the wood and sediment is depositing in the skeleton framework. C. Advanced stage--the original wood framework has become almost completely transformed into knobby-hard ground.



A

B

C

Figure 8. Conversion of pickleweed growth into puffy ground. A. Area of puffy ground that was a former site of pickleweed growth. B. Mounds of living pickleweed alongside area where pickleweed has died and roots have been converted into puffy ground. C. Areas of pickleweed growth being converted into a mound of puffy ground; a few patches of pickleweed (dark-colored plants) remain.

Figure 9. Extensive area of puffy ground in the southern part of Clayton Playa that was the site of former pickleweed growth.

Figure 10. Tailing-Butte Zone, note the horizontal bedding in small hills which have been highly dissected by surface erosion.

Figure 11. Boundary between bedded Tailing-Butte Zone and playa area. Note disruption of bedding in the playa characterized by high capillary discharge.

however, they lose their stratification to become puffy ground within the playa boundary where capillary discharge occurs (Fig. 11). It is noteworthy that capillarity has destroyed this stratification of tailings in the relatively short period of 50 years.

SEDIMENTATION AND HYDROLOGY

Because of its low elevation, Clayton Playa was undoubtedly covered with water during parts of Pleistocene, as were Mud Lake and Big Smoky Playas which occur at high elevations. However, it is noteworthy that Clayton does not have the continuous silt and clay beds which characterize the latter playas. Apparently ground-water discharge, accompanied by deflation, disrupted and removed the silt-clay lake beds, probably by the same processes now destroying the bedded mine tailings on the playa surface. Test hole logs (Fig. 12) from Clayton Playa indicate disturbed and chaotic deposits that are characteristic of playas discharging abundant ground water and depositing abundant salt. Few continuous beds extend through the playa and lake sediments, and correlation is difficult despite the relatively short distance between test holes (generally less than 2,000 feet). A salt zone between 20 and 40 feet deep is the most continuous bed. Silt and clay containing considerable amounts of gypsum and salt are present. Colors of clastic sediments from the test hole range from black through brown to blue; the darker colors probably result from reducing conditions. Below the water level some isolated beds of salt and gypsum are present at shallow depth. The total thickness of alluvial, playa, and lake deposits is not known in Clayton Valley. Rush (1968, p. 15) reports that the deepest known well was drilled through 1,820 feet of unconsolidated alluvial and lake materials and did not penetrate bedrock.

Little is known regarding the details of the hydrogeology and chemistry of water in Clayton Valley. At the playa center no plants can grow because of the high mineralization of ground water. Botanical and hydrologic evidence indicates that relatively fresh water around the margins of the playa

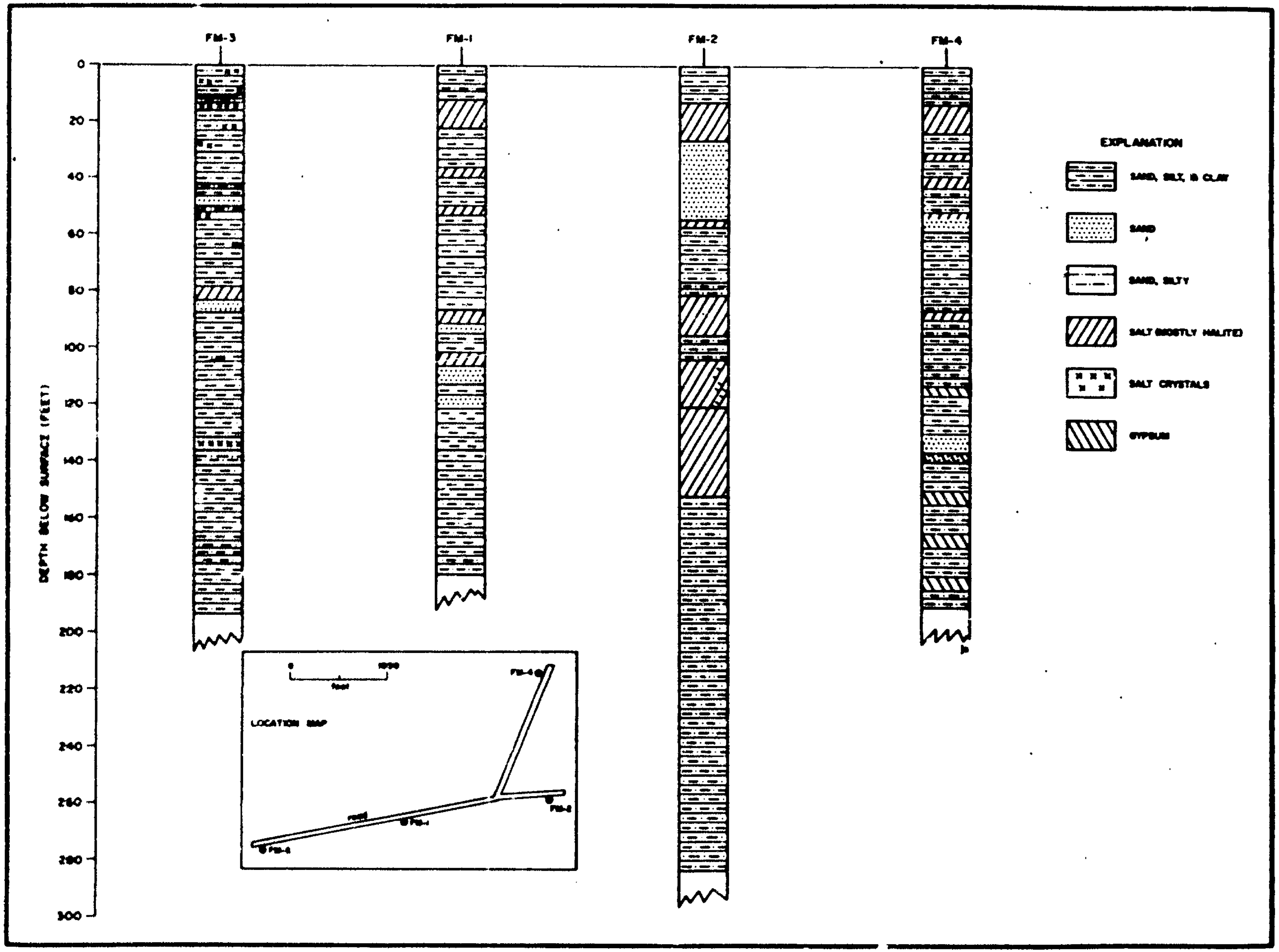


Figure 12. Logs of test holes near central part of Clayton Playa.

grades into the more highly mineralized water near the center. Greasewood and other phreatophytes characteristic of fresh water, merge into pickleweed and salt grass characteristic of more highly mineralized water, toward the center of the playa. Waterworks Springs near the playa margin yields water that is potable enough to be used in the public-supply system at Silver Peak. This is the largest spring in the Tonopah area and discharges about 350,000 gallons per day (Meinzer, 1917, p. 143). Near the center of the playa one of the Foote Company wells yields water with a specific conductance of 242,000 micromhos. This high mineralization of water near the center of the playa is due to the fact that Clayton Playa is the terminal discharging point for deeper water circulation through the adjacent valleys.

Rush (1968, p. 35) calculates that about 22,000 feet of water annually enters Clayton Playa from local precipitation and from subsurface inflow. Since Clayton is a hydrologically closed valley, all this water is discharged by evapotranspiration, spring discharge, and utilization by man. The source of lithium in the ground water is not known; large quantities of lithium-bearing minerals have not been found in the rocks adjacent to Clayton Playa.

CONCLUSIONS

Clayton Valley, which lies at a lower elevation than the nearby Ralston, Alkali Springs, Big Smoky and Fish Lake Valleys, is the terminal discharging area for deep ground-water circulation in the Tonopah, Nevada, area. Consequently Clayton Playa, the lowest part of Clayton Valley, is the site of deposition of much soluble salt which gives the playa its striking white color from a distant view (see frontispiece). A considerable amount of salts is carried by ground water in solution because of the size of the recharge area and the generally long distance between the area of recharge and of discharge.

Logs of closely-spaced test holes show disturbed and chaotic deposits which are characteristic of many terminal ground-water discharging playas. Few continuous beds extend through the playa sediments, and correlation is difficult despite the relatively short distance between test holes. The large amount of ground water and capillary discharge accompanied by deposition of salts has probably disrupted the bedding and lamination of sediments formed in the playa and playa-lake environment. Also by this process, silty mine tailings have been destroyed in the last 50 years. The excellent stratification of the mine tailings abruptly terminates at the playa boundary where capillary discharge has transformed the tailings into puffy ground.

Botanical and hydrologic evidence indicates that relatively fresh water around the margins of the playa grades into more highly mineralized water near its center. From the outer to central part of the playa the following vegetation and water quality changes occur: (1) greasewood and other phreatophytes grow in a relatively fresh water zone and merge into

(2) pickleweed and salt grass growing in a more highly mineralized zone which in turn merge into (3) the playa proper underlain by water of very high mineralization, some of which has a specific conductance of more than 240,000 micromhos. In some places the high mineralization of water is related to the formation of hard and soft irregular puffy ground. Near the center of the playa small areas of knobby-hard ground are formed around the accumulation of twigs, branches and roots carried into the playa by floods. The crystallization of salt derived from surface and ground water, combined with the deposition of mud derived from surface floodings, eventually completely transforms the original skeleton of wood into salt encrusted, hard-knobby ground. In the southern part of Clayton Playa, areas of knobby-soft, salt-encrusted ground are formed by the encrusting of salt and the deposition of silt and mud around pickleweed roots, indicating that the playa may have expanded in this area. Therefore, the boundary between the highly mineralized water underlying the playa and the adjacent fresher water shifts with time.

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CHAPTER 7: SOME HYDROLOGIC AND GEOLOGIC PROCESSES INFLUENCING PLAYA DEVELOPMENT IN THE WESTERN PART OF THE BASIN AND RANGE PROVINCE, UNITED STATES

Ward S. Motts

ABSTRACT

Surface morphology of most coarse-grained and many fine-grained playas is related to several factors, including the rate of capillary discharge and the frequency of surface-water flooding. Puffy ground is present where the rate of capillarity is relatively high and where relatively few floodings occur. A smooth surface is present where the capillary rate is low or lacking and where a relatively large number of floodings occur. On some playas, such as Clayton Playa, Nevada, highly irregular puffy ground occurs in areas of past vegetation growth where capillary discharge combined with deposition of mud from floods has transformed roots and transported plants into highly irregular ground.

During the winter months many playas of the Mojave Desert are frequently flooded; for example, Rogers and Rosamond Playas were flooded in the fall of 1967 and were sites of playa lakes until the spring of 1968. This flooding was accompanied by the following processes that affected the morphology of the playa surfaces. (1) Water on the playa shifted and moved in response to changes in wind direction. (2) Silts and clays near the surface became saturated with water, thereby increasing their mobility. (3) The formation of ice on playa lakes during winter months acted to disrupt and destroy the surface, which further promoted wind erosion. Also as a result of the flooding, numerous playa scrapers were observed whose extensive movement across the playa surface onto the desert flat appears to be one of the factors accounting for the barrenness of many playas.

Geomorphic features on playas constantly change in response to short-term and long-term climatic fluctuations. Daily and monthly changes in microrelief are commonly caused by playa flooding and by seasonal climatic variations. As a result of a single storm in 1964 at Pago Playa, New Mexico, uplifted ridges of evaporite thrust polygons were eroded and dissolved by surface water, and a thin white crust which capped the brown playa silts shifted its position. When the surface was remapped in 1966, the area of thrust polygons was considerably larger than in 1964. Following a major flood, the morphology of Troy surface changed considerably from January 6 to February 6, 1968, as a result of capillary discharge accompanied by deposition of salts. During this period parts of the hard compact surface had been converted into a puffy surface, polygons on the smooth hard compact surface had uplifted and become more concave, and small polygonal cracks had

started to develop on many larger polygons. Many playas, including North Panamint Playa, California, have considerably increased in size in Recent time. The southern part of North Panamint Playa is characterized by puffy, salt-encrusted, oval areas, equally spaced and ranging from a few feet to about 15 feet in width; these barren areas grade in the direction of the desert flat into similar oval areas containing living phreatophytes.

Sediments deposited in the playas of the Mojave Desert are soon removed by wind erosion. Surfaces of Rogers Playa and Rosamond Playa are slowly being eroded and lowered by deflation through the formation and destruction of concave-upward mud polygons. As soon as the polygons are formed, they shear away from the playa surface and are abraded into smaller and smaller fragments by water and wind erosion. The disconnected and loose fragments are easily removed by deflation.

INTRODUCTION

To a casual observer, all playas have similar-appearing surfaces--desolate, barren, and flat; however, upon closer inspection the surfaces range from smooth and hard to puffy and irregular. Each playa has a complex of surface types which makes it distinctive from all other playas. Also, diverse surface types commonly occur within the boundaries of the same playa. This and other chapters discuss the occurrence and origin of the surface types and their change through time.

Our studies show that playas are among the most dynamic of land forms--their geomorphic features reflect daily, seasonal, annual, and secular changes in the environment. These short-term changes in microrelief are caused by several factors of which surface flooding and the amount of capillary discharge are highly significant. Long-term changes of playa types probably relate to climatic cycles, including secular changes that followed the "Little Ice Age." Neal and Motts, (1967, p. 511-525) discuss some of the long-term variations of playa morphology that include playa expansion, formation of giant desiccation polygons, and the development of micro-karst topography in playas containing evaporites. Because many features on playa surfaces are "relics" of a former climate, study of these features can yield valuable insight into past climates and environments.

PLAYA-SURFACE TYPES

The great diversity of playa surfaces and their continuous modification are caused by many factors. Knowledge of processes producing many of the surface types was gained through the present study; however, only a beginning has been made in completely understanding the many complex processes that are related to the origin of all playa surfaces. The behavior of playa surfaces is closely related to (1) the gross texture of the playa sediments and (2) the amount and frequency of flooding and the amount and nature of capillary and ground-water discharge.

Puffy ground occurs on many coarse-grained playas because they now have, or have had in the recent past, a shallow water table. Consequently, the surfaces of these playas have been subject to capillary discharge which in turn is the primary cause of the puffy surfaces. Ground water readily moves and discharges through sediments of coarse-grained playas. Some factors that control the occurrence of shallow ground water and its discharge rate are beyond the geographic limits of the playa and include height and extent of the recharge area and the permeability of sediments through which the ground water travels.

Langer and Kerr (1966, p. 379) point out that some coarse-grained crusts with high saline content can assume the characteristics of puffy ground when wet by precipitation. These authors (p. 378-380) also classify playas by texture and mineralogy and conclude that puffy surfaces are underlain by silt and sand with a granular texture, whereas compact, smooth surfaces are underlain by fine-grained silt and clay. However, this study reveals that some playas with puffy surfaces (for example, Big Smoky Playa, Nevada, and Coyote and Lucerne Playas, California) are

underlain by fine-grained silt and clay. Neal (1968, p. 29) concluded that the development of puffy surfaces on Harper Playa was favored by crusts with granular texture, but the puffy-surface development was not affected by mineralogic differences.

Playas commonly develop a smooth, hard surface where the capillary rate is low or lacking and where a relatively large number of floodings occurs. Even in playas characterized by high capillary discharge, such as Columbus Marsh, Nevada, smooth, hard ground may form in areas such as stream channels having many floodings (Fig. 1; also see Krinsley, 1968, p. 108-111). On the other hand, coarse-grained playas and many fine-grained playas develop puffy ground where relatively few floodings occur and where the rate of capillarity and ground-water discharge through the surface is relatively high. Discharge through the surface is accompanied by evaporation and deposition of saline salts which disrupt and disturb the surface, thus producing puffy ground. Our studies indicate that, other hydrologic and geologic parameters remaining constant, the micro-relief of puffy ground increases with higher mineralization of capillary water--an empirical observation that should be verified by further detailed quantitative studies. Langer and Kerr (1966, p. 382) related the amount of disruption of a playa surface to the amount of saline minerals present.

Thompson (1929) and Stone (1956, p. 66) concluded that puffy ground is caused by capillary movement from a shallow water table--a relationship that has been substantiated in this and in other chapters of our publication. Our study also reveals that a shallow water table is not a necessity for the formation of puffy ground if water under artesian head is discharging from the playa at depth. Furthermore, many playas have areas of puffy ground

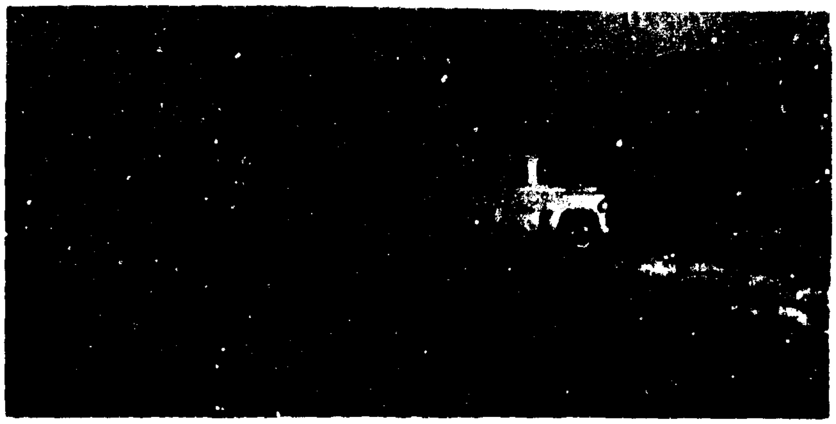


Figure 1. Smooth, compacted ground along wash in Columbus Marsh, Nevada. Photograph by James T. Neal.

Figure 2. Area of wet salt-encrusted surface on South Panamint Playa which is part of a high transmissibility zone.

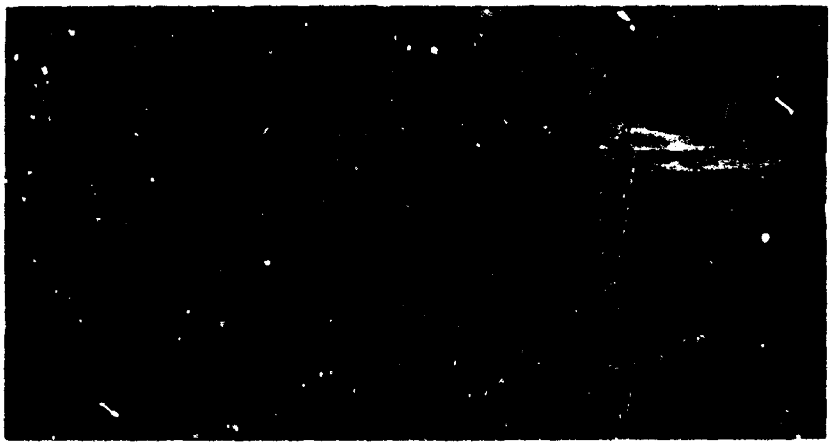


Figure 3. Hard surface to south (left) of Ballarat Road, which dammed flood water and produced the consolidated surface. Puffy surface to north (right) of South Panamint Playa Road.

that are a relic from a time when a shallow water table was higher or when the artesian head was higher and consequently the rate of ground-water discharge was greater.

The relationship of puffy ground to capillary discharge was demonstrated at Troy Playa, a coarse-grained playa, and at Big Smoky Playa, a fine-grained playa. At Troy the presence or absence of puffy ground is related to the occurrence of sand lenses in the playa sediments (Groat, Chap. 5, p. 189-191). Where the water table lies within sands, little to no capillary discharge occurs and the ground is smooth; on the other hand, where the water table is in the finer-grained silts, capillary discharge occurs at the surface and forms puffy ground. At Big Smoky Playa (Walker and Motts, Chap. 4, p. 164) the presence of puffy ground is also related to the occurence of sand lenses in the playa sediments. Where sand lenses are present, they become filled by upward-percolating capillary water from deeper aquifers under high artesian head. Water discharges from the shallow-sand aquifers by capillarity at the surface, and causes formation of puffy ground. Conversely, where no lenses are present capillary discharge occurs at a much smaller rate resulting in a hard, smooth surface.

Some playas which formerly had porous, puffy ground now have smooth, compact ground because of a decrease of capillary discharge caused by a lowering of the shallow water table or the deeper potentiometric surface. For example, Rogers and Rosamond Playas had puffy ground in the early 1900's when the potentiometric surface was higher and large amounts of capillary discharge occurred. Now, however, small amounts of capillary discharge occur because the potentiometric surface has dropped within the playa and lake clays, and floodings of the playa have been effective in transforming the surface into smooth, hard ground. Lucerne Playa is also undergoing a

transformation from puffy ground into smooth ground because of a lowered potentiometric surface. Neal (1968, p. 29) found that most of Harper Playa was converted from a soft, dry, friable surface in 1962 to a hard, dry surface in 1967 because of a lowered water table.

Puffy ground can form from processes other than capillary discharge. On Clayton Playa, areas of highly irregular puffy ground occur where vegetation, mostly pickleweed, lived (Motts and Matz, Chap. 6, p. 224). When the pickleweed died, capillary discharge, combined with surface-water deposition, transformed dead roots into soft puffy ground. Other areas of hard puffy ground are caused by the encrustation of salt and deposition of silt and mud around accumulations of twigs, branches, and roots carried into the playa by floods. The origin of puffy ground in some extremely fine-grained playas such as Coyote Playa has not yet been completely resolved. Hagar (1966 and Chap. 3, Pt. 1) concluded that the puffy ground of Coyote Playa not associated with nearby marginal zones is the result of surface water infiltrating, moving through, and interacting with very shallow playa sediments, whereas Motts (Chap. 3, Pt. 2) presents an alternate view that the above-mentioned puffy ground is due to slow discharge of ground water through the playa surface by capillarity and artesian head.

During the course of this investigation, evidence of zones of higher transmissibility were observed in seemingly homogeneous playa and lake deposits. South Panamint Playa, underlain by silt, clay, sand, and evaporites, is characterized by some areas of high transmissibility where relatively large amounts of ground water discharge and produce soft, moist sediments (Fig. 2). The extent and cause of these lateral variations of transmissibility in playa sediments is not known but they may cause unexplained areas of puffy ground observed on some playas; therefore, these variations should be studied further in future investigations.

HYDROLOGIC CONTROL OF SHORT-TERM CHANGES OF PLAYA SURFACES

Numerous coarse-grained and fine-grained playas are sites of a continuous conflict between surface-water and ground-water processes. Surface-water processes tend to produce a hard, smooth, playa surface, whereas ground-water processes are constantly converting this latter surface into puffy, self-rising ground. The effects of this conflict are especially evident in playas characterized by a high rate of capillarity where a single flooding can profoundly affect the playa surface. At such playas several floodings can completely alter extensive areas of irregular puffy ground into a flat, smooth, firm surface. Some of the effects of floodings on Troy, South Panamint, and Pago Playas are discussed in this section.

The conversion from puffy into hard, smooth ground as a result of flooding was responsible for the striking difference between the north and south side of Ballarat Road, South Panamint Playa in 1966 (Fig. 3). Standing flood water, dammed by the road on the south side, had consolidated puffy ground into the smooth, hard ground at the site of two Air Force test holes (Motts and Carpenter, 1968, Fig. 13). The "billiard table" aspect of the surface in 1966 allowed rapid unimpeded travel by vehicles. However, when the area was revisited in the winter of 1967-68, large irregular areas of moist puffy ground had formed on the previously smooth surface (Fig. 4). The areas of puffy ground, with microrelief ranging from one to four inches, ranged in size from a few feet to several hundred feet across. The hard, smooth surface gradually graded into the areas of mature, well-developed, self-rising ground that contained numerous openings through which capillary discharge occurred. The striking conversion from hard, compact ground to puffy ground had occurred in a period of 1 1/2 years.

A

B

C

Figure 4. Hard, compact ground converting into puffy ground near test hole site, South Panamint Playa. In summer 1966, this entire area was hard, compact ground--(A) irregular area of newly developed ground. (B) Hard, compact ground grades into (C) core of puffy ground.

Troy Playa

When I visited Troy Playa in January 1968, the surface was still wet from extensive flooding in November 1967, which may have caused much of the hard consolidated surface. From January to February 1968, the morphology of the playa surface changed in the following ways (Fig. 5): (1) parts of the hard, compact surface had been converted to a puffy surface; (2) polygons on the smooth, hard, compact surface had become uplifted, more concave, and their edges had curled upward; (3) small polygonal cracks had started to develop on many larger polygons; (4) numerous polygonal shreads had formed in places; (5) parts of the surface, rather than being flat, were now wavy and characterized by small rises and depressions; (6) irregular areas of salt encrustation had become scattered throughout parts of the surface; and (7) irregular masses of puffy ground had formed small linear hills adjacent to a jeep path on the playa surface (Fig. 6). The hills indicate ground-water discharge is occurring through the playa surface; capillary discharge is reduced by the compacted sediments beneath the road and diverted to discharge through the more porous sediments at the road margin.

In February, some of the original hard surface, mapped in January, had been changed into isolated patches of knobby, puffy ground; and the older polygonal mud crack surface was becoming destroyed and reconverted into the original puffy ground surface that is characteristic of this part of Troy (Fig. 7). In January, polygons on the hard, compacted surface were separated from each other by only a fraction of an inch; however, in February many of them had been uplifted and were separated from each other by distances ranging from 1/8 to 3/4 of an inch. The polygons were approximately 6 inches to almost 1 foot across and their cracks were 1/2 to 3/4 of an inch

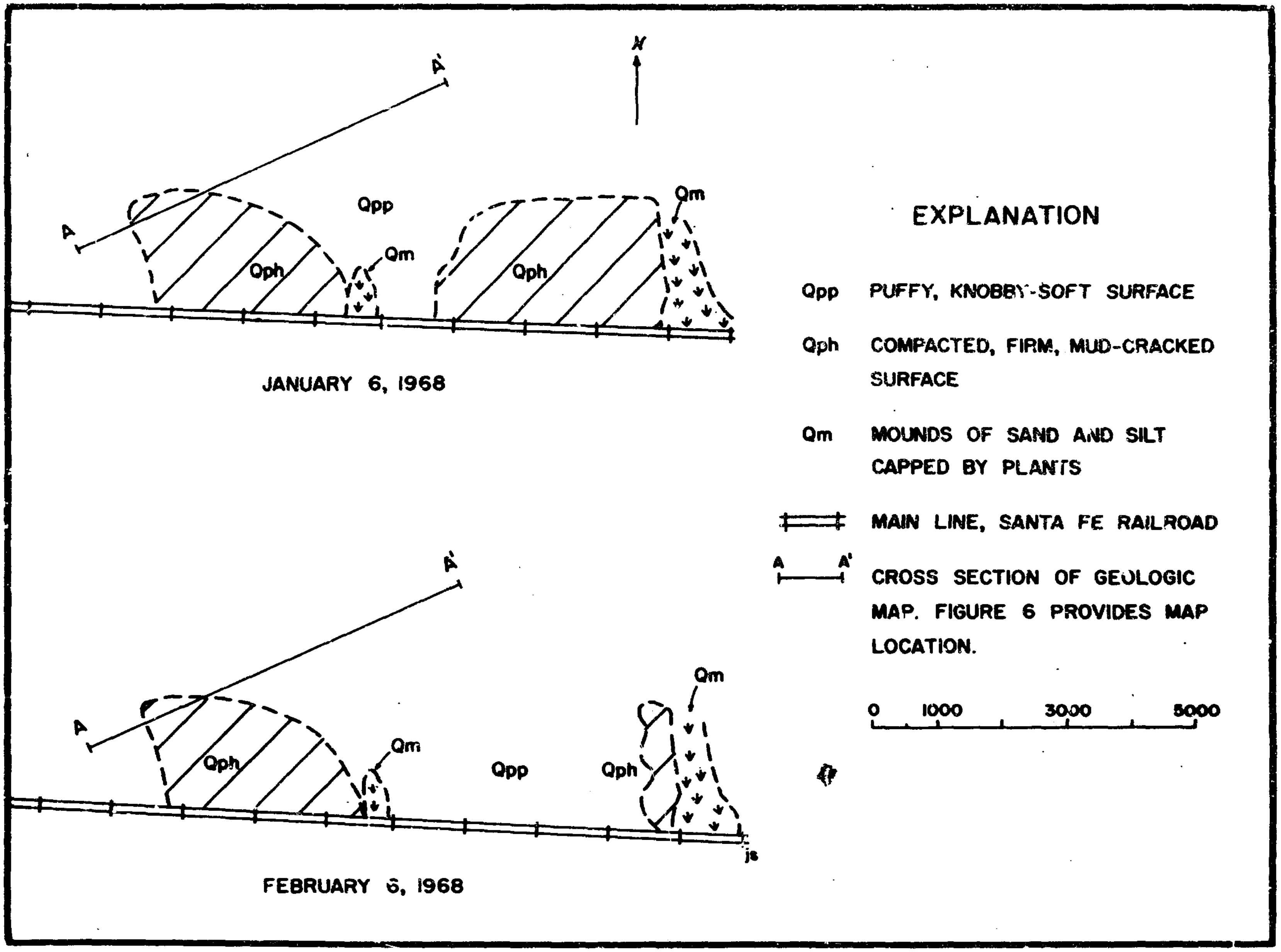
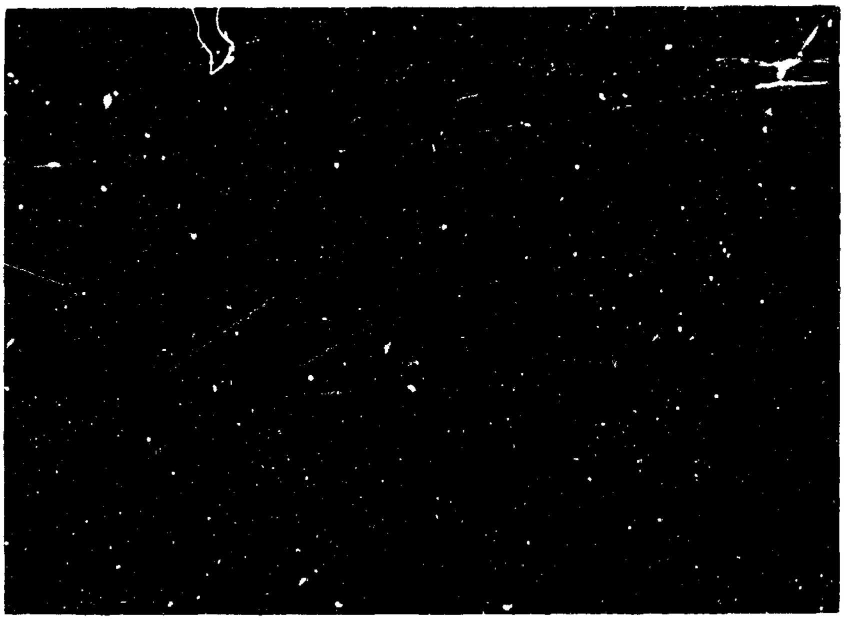
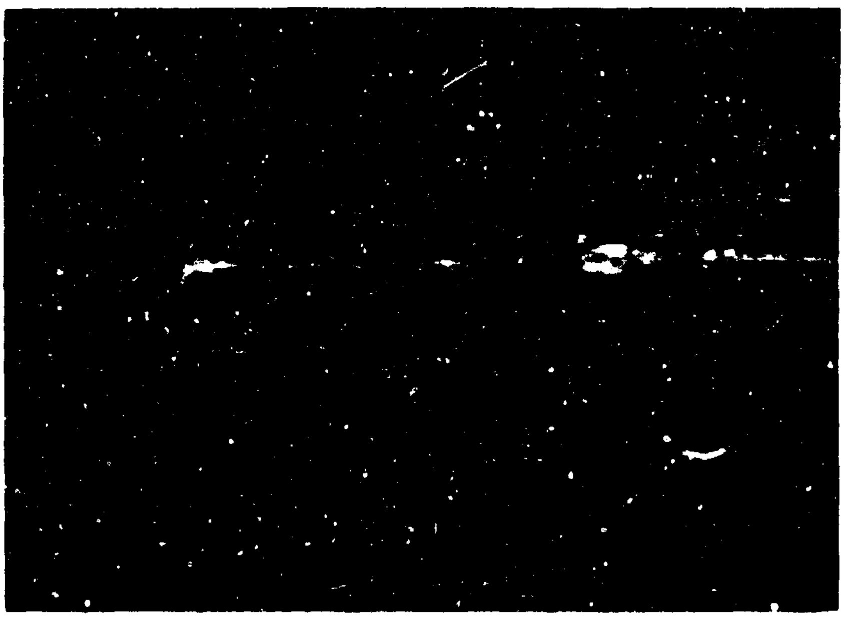


Figure 5. Changes on surface of Troy Playa, California from January 6 to February 6, 1968.

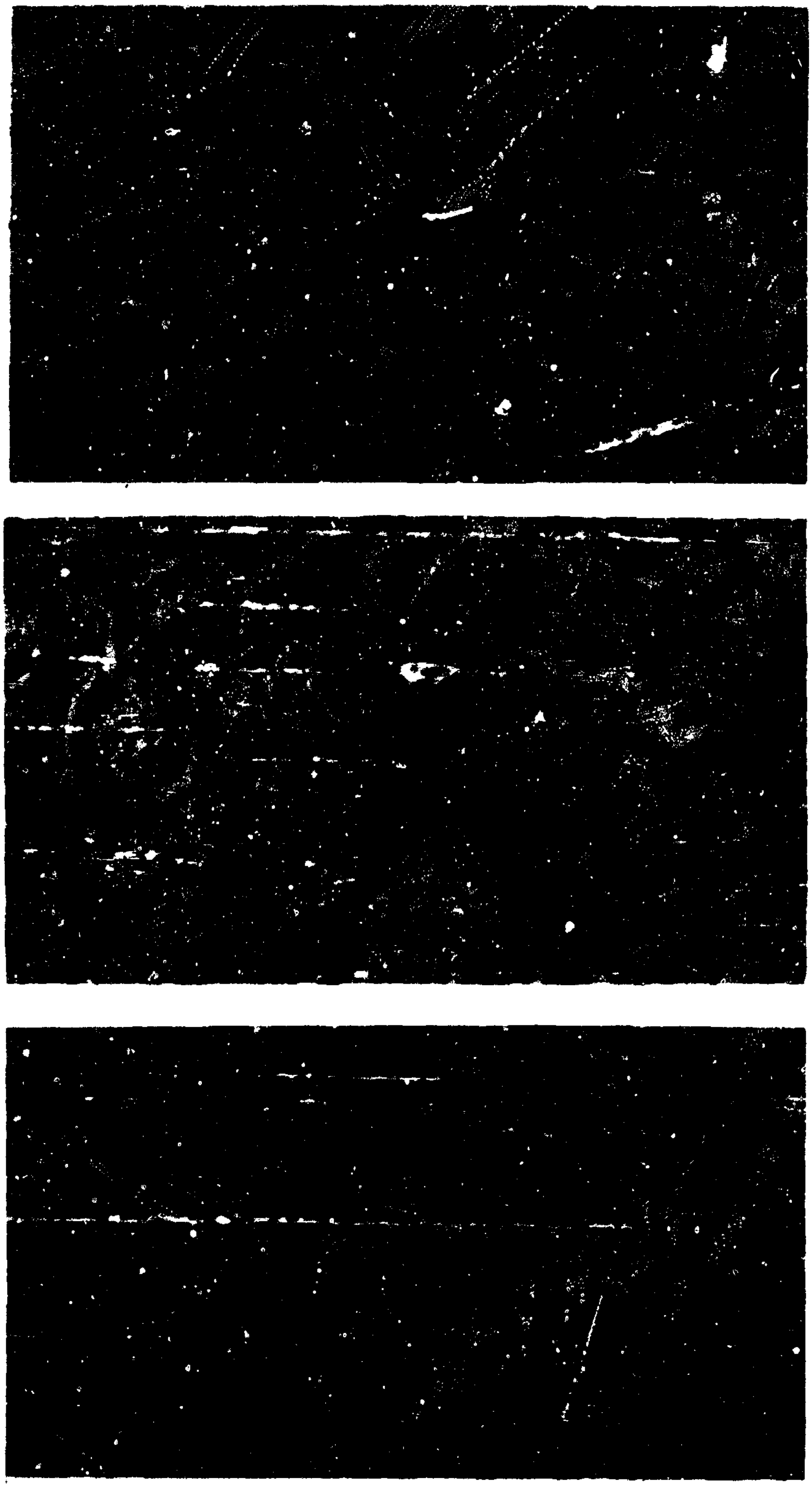


A



B

Figure 6. A. Puffy ground along jeep road on Troy Playa, California: capillary discharge occurs along compacted areas of many playas in the Mojave Desert. B. Close-up of puffy ground shown in the above photograph.



A

B

C

Figure 7. Changes on Troy Playa, California--surface from January 6 to February 6, 1968. A. Hard surface on Troy formed from surface-water consolidation. Areas along fractures are uplifted from deposition of salts accompanying capillary discharge. B. Hard, compacted ground converting into puffy surface. Note upturned polygons along fractures and smaller polygons formed on larger polygonal set. C. Old, compacted surface has almost completely changed into puffy ground.

deep. The greater distances of crack separation observed on February 9 appeared to result from the raising and heaving of the playa surface from capillary discharge and concomitant deposition of salts. Also salt deposition along the polygonal cracks probably caused mud polygons to uplift, to separate, and to form their characteristic concave shape.

In January the entire western playa-area had a hard, light-brown surface and a checkered appearance due to areas of relatively deep polygons. The polygonal cracks had separated to distances of 1/16 to 3/4 inch, and to depths of 1 to 5 inches. In one part of the playa, mud polygons stood as small buttes and were as much as 4 to 5 inches high and 1/2 to 3/4 inch across. The small buttes were themselves fractured into numerous smaller polygons about 1/8 to 1/4 inch across. The surface appeared to be fracturing into finer and finer particles, a process that I observed also at Steptoe Playa, near Ely, Nevada.

Large areas of the playa surface had changed from flat to gently rolling. The microrelief ranged from about 1 inch to 1-1/2 inches, averaging about 1 inch. This heaving action had also separated the fractures along the polygons as described below. Irregular areas of white salt not present in January were scattered throughout the brown surface in February. Apparently surface salt that had been removed by floodings and by deflation were being reestablished on the playa. Similar observations were made by Groat (personal communication).

An important change on the surface of Troy was the new appearance of numerous small polygonal shreads that had developed since January. The shreads were commonly a fraction of an inch thick and were from 1/4 to 1/2 inch across. Within a month, many of these shreads had formed and had been

deflated from the surface. The flaking off and deflation of surface-sediments may be facilitated by the thin-bedded nature of the sedimentation units underlying Troy Playa. Each unit is characterized by sediments of a different texture which facilitates the formation of shear zones between the sedimentation units.

Pago Playa, near Estancia, New Mexico

From 1963 to 1970 I studied Pago Playa, one of the playas in Estancia Valley, several times and each time found the surface had changed from its former condition. Basically, the playa has three major surface types which change in response to differing climatic conditions (Figs. 8 and 9): (1) a smooth brown surface with little salt stain occupying the outer margin of the playa, (2) a salt-encrusted, white-to-cream surface underlain by dark, wet silt that nearly coincides with the top of the zone of saturation, and (3) a zone of "thrust polygons" or "pressure polygons" that generally forms in the southern part of the playa (Fig. 10). In April 1966 the pressure polygons had ridges up to 1-1/2 inches high where they were most fully developed.

The changes in playa-surface morphology are related to (1) the frequency, extent, and depth of playa floodings, (2) the length of time between floodings, and (3) the season. Minor floods dissolve most of the white salt crust throughout the playa and expose the underlying brown area. Part of the salt escapes into the atmosphere as flood water evaporates and part is redeposited as a salt crust in the low southern part of the playa. However, continuous capillary discharge is soon responsible for an expansion of the salt-encrusted area and the development of pressure polygons which slowly form along fractures in the salt crust. Deposition of salt along the fractures causes the adjacent crust to uplift into the characteristic pressure

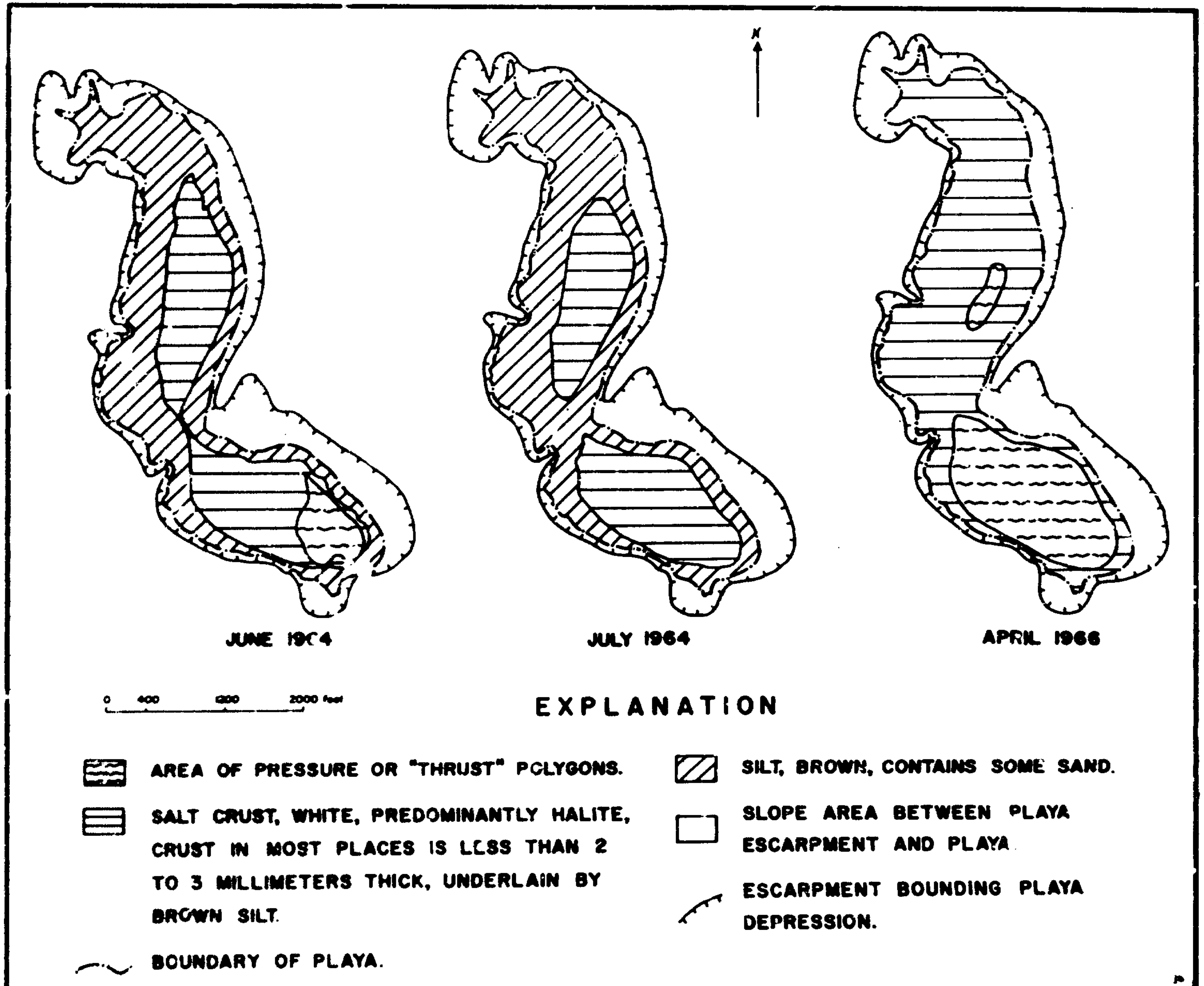


Figure 8. Map cf Pago Playa, New Mexico, showing shifts of playa surface types in 1964 and 1966. (Mapped by W. S. Motts.)

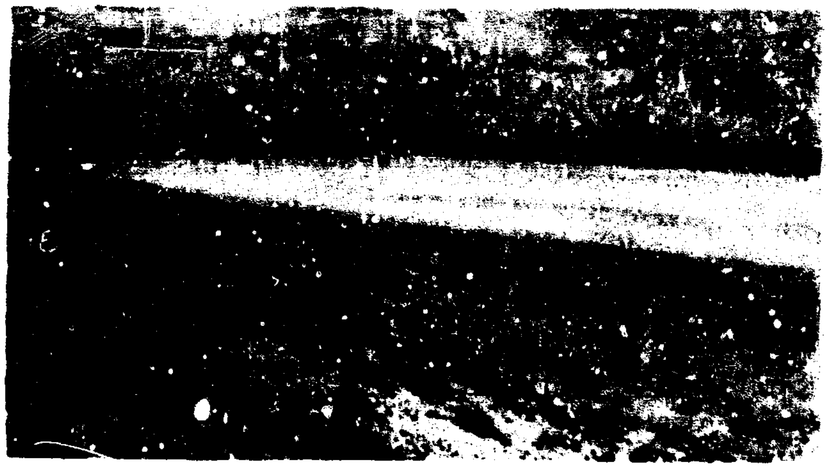


Figure 9. Pago Playa, looking eastward across the brown, smooth surface to the salt-encrusted white cream surface.

Figure 10. Uplifted crust of typical pressure polygons on Pago Playa, New Mexico, June, 1964, before flooding.

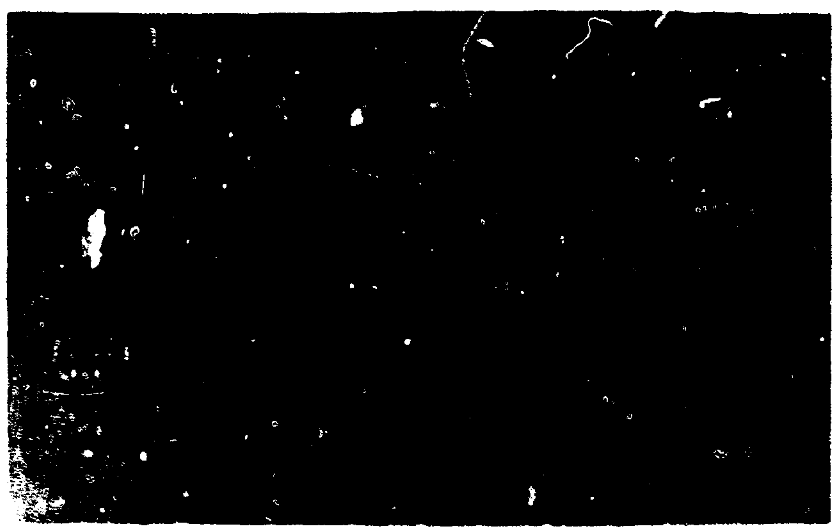


Figure 11. Truncated base of pressure polygon after flooding in August 1964.

polygons (Fig. 10). The size and area of pressure polygons and the area of the salt-encrusted ground increases with successively longer times between floodings and increases during the summer when the evaporation rate is greater.

Major changes of surface morphology as the result of a single storm in August 1964 are shown in Figure 8. First, uplifted ridges of the evaporite pressure polygons were eroded and dissolved by surface water, exposing the mud cores of the polygons (Figs. 10 and 11). Secondly, the thin, white crust capping the brown playa silts shifted its location. In April 1966 I again visited the playa and found that the surface had completely changed. There were no floodings from January to April 1966; consequently the salts accumulated and the area of pressure polygons greatly expanded.

SOME INFLUENCES OF SURFACE-WATER FLOODING ON PLAYA SURFACE MORPHOLOGY

Playas of the Mojave Desert are frequently flooded during the winter months. The floodings produce significant changes on their surfaces, including the conversion from puffy to hard ground, discussed in the previous section.

Rogers and Rosamond Playas, flooded on November 24, 1967, were sites of playa lakes until the spring of 1968. Flooding of the two playas modified their surface morphologies by the following processes. (1) Water moved and shifted on the playa surfaces in response to changes in wind directions. (2) The mobility of playa surficial materials was increased due to saturation by surface water. (3) Ice formed at times on the lakes and disrupted the playa surfaces. Also as a result of the floodings, numerous playa scrapers moved and left their trails on the surfaces of both playas.

Shifting of Water on the Playa Surface

Every time wind of moderate velocity shifted in direction during January and February 1968, there was an accompanying major shift of water movement on Rogers surface (Table 1 and Figure 12). Water movement across the flat playa surface is somewhat similar to a fan blowing water across a smooth table top; the extreme flatness of the table top and of the playa greatly facilitates movement of water. Mr. Joseph Reif of Edwards Air Force Base (oral communication) reported that a 42 mph (miles per hour) wind on January 10 moved the surface water across the playa at a rate of 6 feet per minute, and a wind on January 20 moved the water at a rate of 3 to 4 feet a minute. On February 5, I observed a gentle wind of less than 6 miles per hour moving water across the playa surface at the rate of about 1 foot in every 4 or 5 minutes (Figs. 13 and 14).

TABLE 1

Surface Water Movement on Rogers Playa

DATE	WIND VELOCITY	REMARKS
Dec. 7	Average 16 mph (miles per hour), high 43 mph from west	Water moved from northwest to northeast part of playa--from A to B on Fig. 12.
Dec. 9	17 mph from northeast	A large volume of water moved from B to A (northwest) on Fig. 12.
Dec. 13	40 mph from north	
Dec. 14	30 mph from northeast	More water moved from B to A.
Jan. 10	42 mph from northwest	Moved large volumes of water from A to B northeast--water movement at one time reported to be 6 feet per minute.
Jan. 16	35 mph from northwest	More water moved from B to A.
Jan. 18	14 mph from northwest	Moved water from B to A (northwest). Also moved water from northeast C to southwest D.
Jan. 21, 22	23 mph from northeast	Moved more water from C to D.
Jan. 26, 27	18 mph from east	Moved water from B to A.
Jan. 31	33 mph from west	Moved water from B toward A and from D toward C.

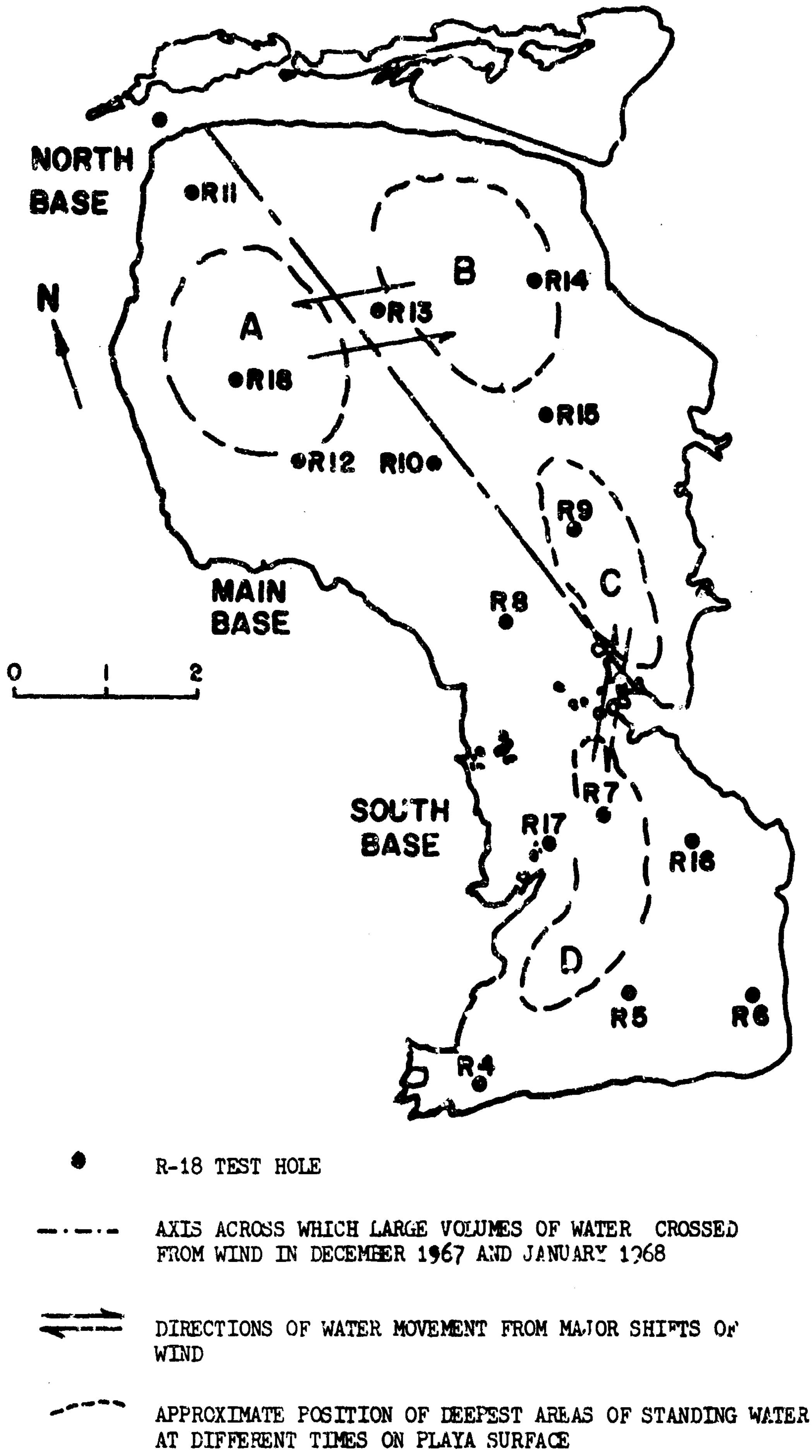


Figure 12. Map of Rogers Playa showing principal directions of shifting flood waters.

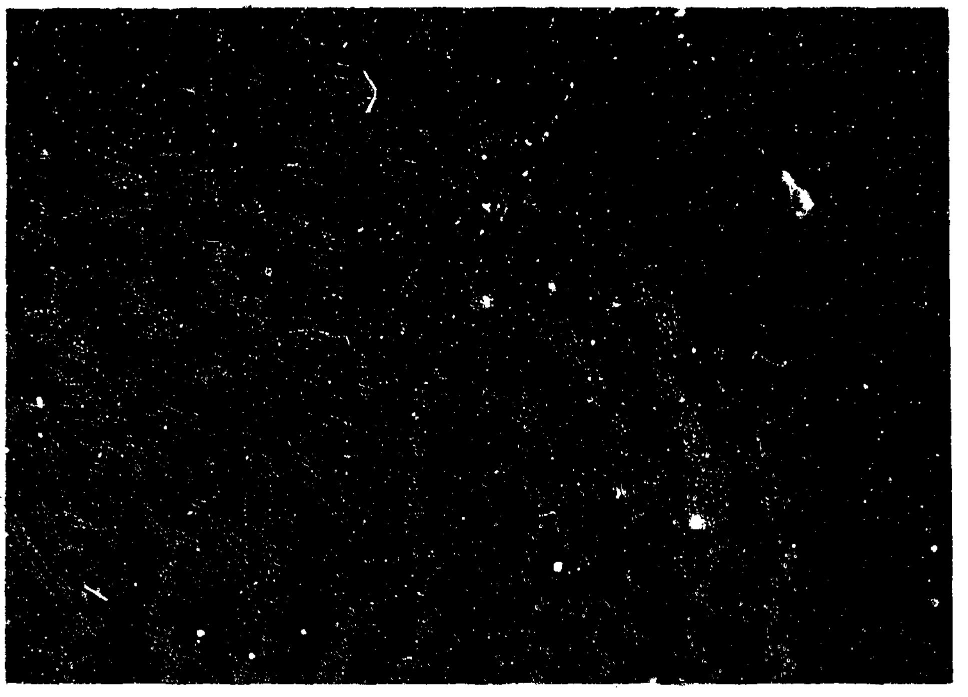


Figure 13. Surface water moving by wind in the north central part of Rogers Playa.

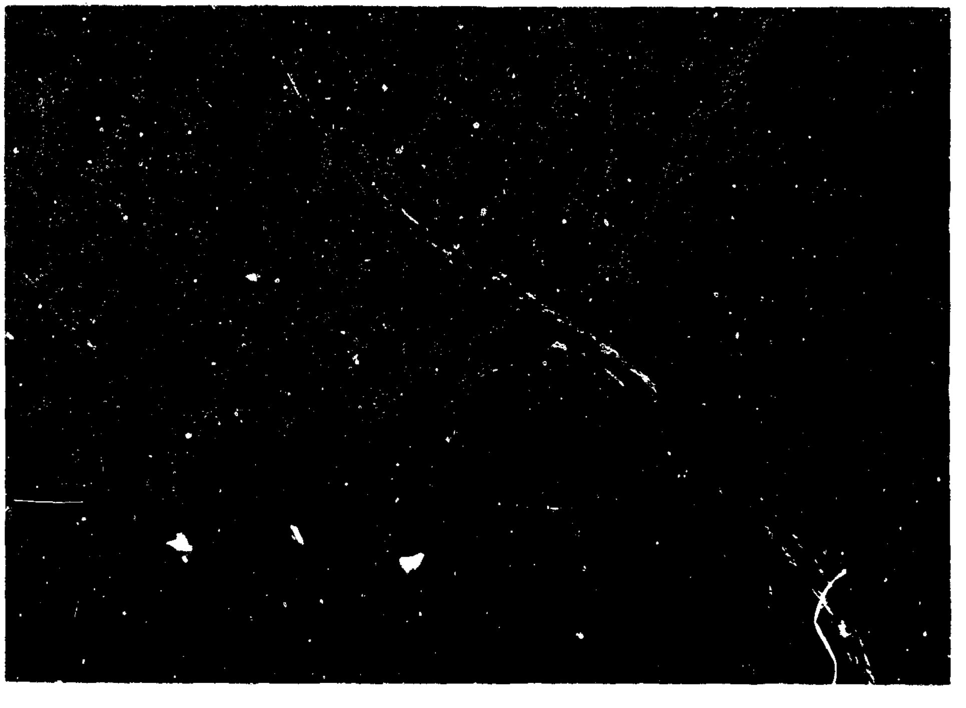


Figure 14. Same locality as Figure 2 but 4 minutes later. Note movement of water in relation to pencil. Water is moving at a rate of about 1 foot every 4 or 5 minutes.

The moving water eroded small flakes and particles of mud curls and carried them in the direction of water movement. The small flakes resembled swimming brine shrimp which were also present in the playa lake at that time.

Shifting of water back and forth on Rogers Playa was effective in smoothing out irregularities of the surface. For example, in September of 1967, deep ruts, 3 to 4 inches deep, were made by a B-52 aircraft in the north-central part of the playa. By January, the ruts had become filled in and were practically smooth after water had moved back and forth over the rut area (Fig. 15). The movement of water is probably also accompanied by mud flow or mud creep for reasons given in the next section.

Saturation of Surficial Fine-Grained Sediments

Surficial fine-grained sediments are changed into a semi-liquid condition after prolonged contact with flood water in playa lakes. This was observed on Rogers Playa at the site of R 10 (Fig. 16) after water had been on the surface two months. A depressed area around R 10 contained water and mud about 3 feet deep in which brine shrimp were living. Muddy water near the surface graded downward through watery mud into solid mud at that depth. A thin crust of clay rested on the muddy water.

Saturation of the fine-grained sediments appears to be accompanied by the following processes: (1) Water is retained around the clay-mineral particles, in the pores between the particles, and between the unit-cell layers of particles (Grim, 1953, p. 161). The latter process causes swelling of most montmorillonite--a clay mineral that occurs in considerable amounts in the sediments of both Rogers and Rosamond. Thixotropic conditions may accompany the saturation of the clay minerals. Kerr (oral communication) indicated that in some cases the assemblege and mineralogy of

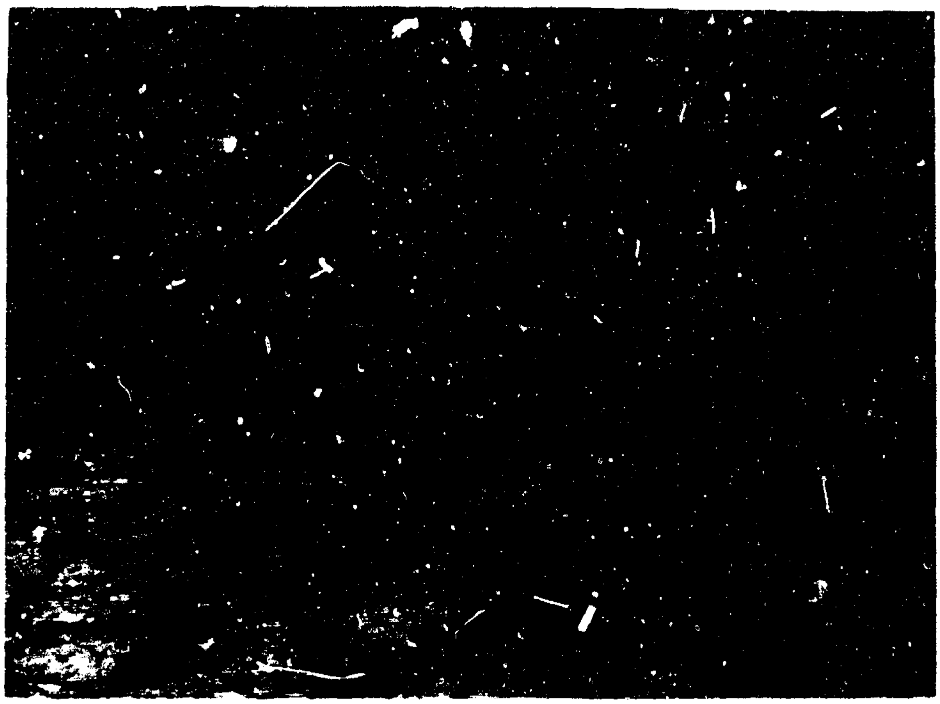


Figure 15. Tracks of B-52 aircraft smoothed out by moving surface water on playa surface. The impressions were originally 3-4 inches deep.

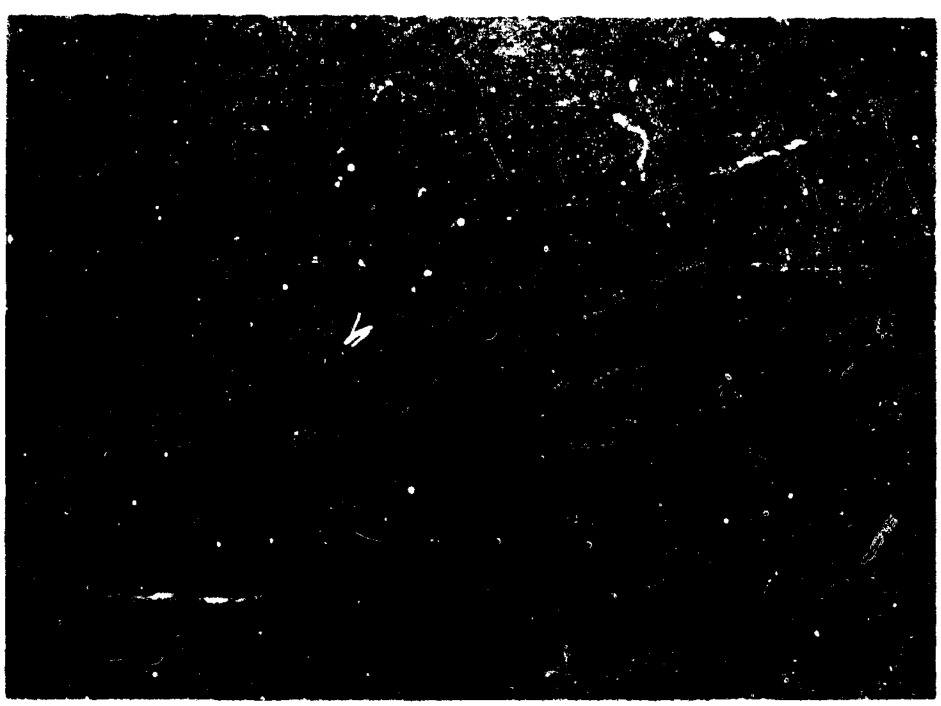


Figure 16. Depression near Test Well R 10, containing viscous water and watery mud that grades into soft mud. Brine shrimp were swimming near surface.

clay minerals in desert playas is similar to "quick-clay" deposits of more humid areas. (2) The process called "slaking" (Terzaghi and Peck, 1948) commonly causes the surface clay to shear away from the underlying clays. Water on the playa surface rapidly enters the sediments by high capillary action; the water compresses the air of the soil pores producing a plane of wet clay near the surface and dry clay at depth. The reaction of the pressure of the compressed air in the pores can cause disintegration of the clay which further increases its porosity and probably results in more of the clay being taken into suspension. (3) Relatively large amounts of salt, accumulated through capillary solution, may force small particles of clay into suspension. The author has observed that rain water on the playa surfaces of Rogers and Rosamond is immediately clouded with fine particles of clay and silt. David Carpenter (manuscript in preparation) has made some similar observations.

The saturation of the fine-grained sediments greatly increases their mobility and consequent tendency to move across the playa surface; mud flows, and/or soil creep accompany the rapid shifting of surface water across the playa. It has been noted in an earlier section of this report that deep aircraft ruts and giant desiccation cracks have been smoothed out in the months following a major flooding of Rogers Playa. Closing of giant desiccation cracks by sediment flow appears to be restricted to the near-playa surface, since the surface water from other major storms erodes the shallow "sediment shell" and reopens the cracks. The above process has been observed many times on Rogers Playa as well as many other playas.

Sediment flow and/or "quick clay flow" may be one of the processes that causes the extreme flatness of playas. I have observed chaotic breccia zones

a few inches thick enclosed in normal thin-bedded playa and lake beds in the test cores from Rogers, Coyote, and North Panamint Playas. The breccia zones may have formed from mud flows following playa flooding.

Ice Formation on Playa Lakes

Playa surfaces appear to be weakened and shattered by alternate freezing and thawing of the playa lakes during the winter. I observed that the playa lakes of Rogers and Rosamond often completely froze after a period of subfreezing weather. Also, areas of shallow water on playa lakes froze during the night and thawed during the day; similar observations have been made by personnel at Edwards Air Force Base. This alternate freezing and thawing disintegrated and shattered the playa-surface sediments, especially where ice formed in desiccation cracks and other openings on the surface.

The amount of deflation greatly increased during the winter and early spring of 1967-68 following flooding and freezing of water on the surface of Rogers, Rosamond, and Coyote. At this time, moderate winds were observed to carry clouds of the fine-grained materials into the air; also, thick columns of dust followed vehicles that crossed the playa. On the other hand, much smaller amounts of dust rose behind vehicles on Rogers Playa in the summers of 1963-66, indicating that less wind erosion was occurring.

Playa Scrapers

During the winter of 1967-68, numerous playa scrapers and their trails were observed on Rogers, Rosamond, and North Panamint Playas. Many scrapers had moved 30 to 60 feet and some more than 200 feet. I observed about 25 playa scrapers in all parts of Rogers Playa and about 50 scrapers on North Panamint Playa during field study in January 1968. Some of the scrapers in the southern part of Rogers Playa had trails that extended for hundreds of feet (Fig. 17). Most scrapers were gravel; however others were miscellaneous fragments of iron, bushes and sticks.

A construction road was built from Rosamond Boulevard into the central part of Rosamond Playa. Following extensive flooding of the playa on November 24, waves from the playa lake washed many gravels from the road into the lake. The gravels ranged from less than 1/4 inch to more than 4 or 5 inches across; some of them were washed several hundred feet into the playa. Forty or fifty of the rocks as well as stones, pieces of iron and sticks moved across the playa surface as water in the playa lake started to evaporate in December 1967. I had an opportunity to observe continued movement of the scrapers near this playa road during December 1967 and January 1968. On December 8, playa scrapers were first observed to move when the lake in this part of the playa had been reduced by evaporation to a depth of about 1-1/2 inches. On the morning of December 8, when water had frozen to a thin crust in the vicinity of the road, trails of playa scrapers were observed in the mud under the ice crust and shallow water. A small ridge of mud near the front of some gravels indicated they had been pushed through the mud (Fig. 18)

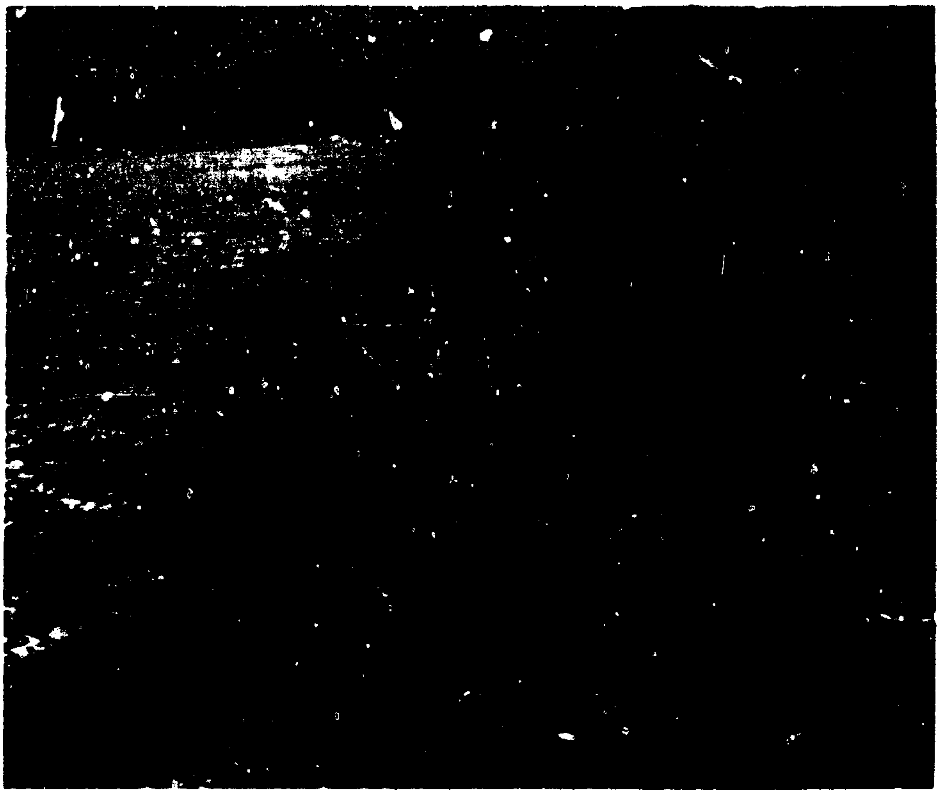


Figure 17. Playa scraper trail more than 100 feet long in north central part of Rogers Playa.

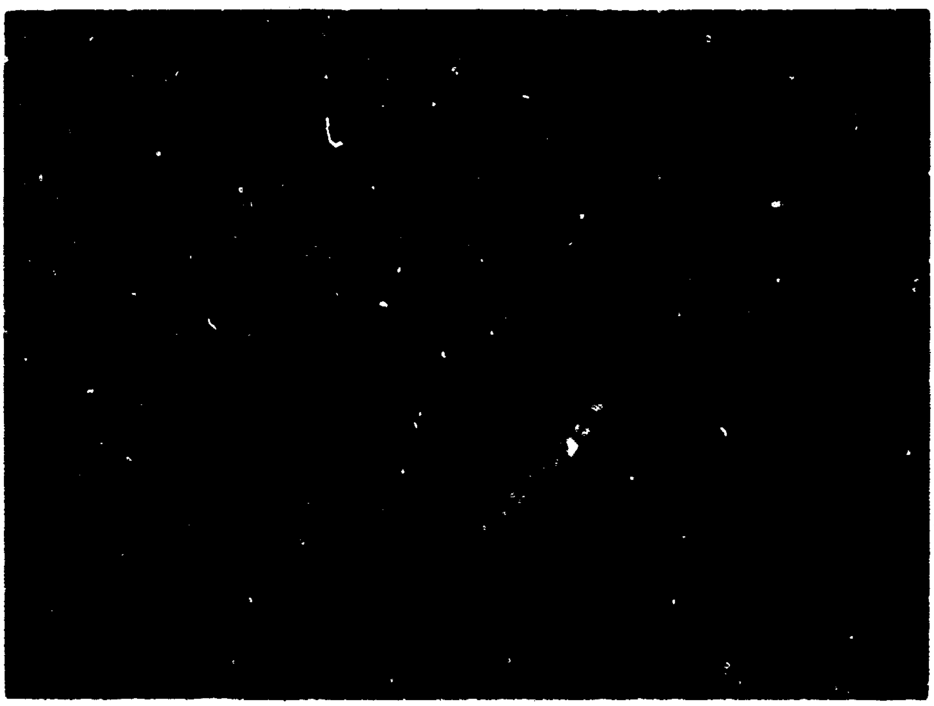


Figure 18. Playa scraper near construction road on Rosamond Playa. Note ridges of mud around front of scraper and crack formed along scraper trail from dessiccation of mud.

It was interesting and somewhat puzzling as to why scrapers from each side of the road moved toward the road; gravels south of the road moved north and those north of the road moved south. Also some gravel south of the road moved eastward parallel to the road. Trails were observed behind 30 or 40 scrapers. Many of the scrapers which had moved across the surface were resting between 3 inches and 1 foot above the playa surface on the road embankment, indicating that the process producing the movement had considerable force. Ice thrusting may be the process with the ability to push scrapers up and onto the shore. Ice formation may also explain why scrapers moved toward the road from each side of the playa lake. The formation of ice may have started near the center of the playa lake and progressed closer to the shore, thus pushing the scraper landward.

Preservation of the scraper trails occurred when the critical depth of water was 1/2 to 1 inch deep during the drying-up of the lake. The trails were not observed when water depth was more than a few inches either because movement did not occur or because the waves in the playa lake and/or mud flows on the playa surface effaced all evidence of movement. Also movement did not occur when the water had completely evaporated to a dry mud flat.

The movement of scrapers may be related to the length of time that water rests on the playa surface; when water is in contact with clays for a long time the clays are transformed into a semi-liquid state. The thixotropic condition of the clays may be a factor in the movement. On Rosamond Playa clays beneath a crust of ice had the appearance of a "quick-clay" state; when one touched the clays they were almost fluid. The pressure of the moving scraper may change part of the mud to fluid. Playa scrapers, sticks, or any other objects on the playa surface are probably transported

in the viscous mud-water suspension. The bottom of the scraper lies in the solid but soft clay and makes a trail in the soft clay as it is carried along in the overlying suspension. Many gravel clasts which are firmly imbedded in playa muds are forced out of their resting position by shifting water of playa lakes. Figure 19 shows one such clast on North Panamint Playa that has moved and left a trail from its resting position. The hollows left by the vacated clasts range in size from a half inch to more than a foot across; in places, the hollows are several inches deep. Figure 20 shows numerous hollows left by the vacated gravel in the southern part of Coyote Playa. These hollows are in a smooth, hard area where flood water from Coyote Wash has compacted the playa materials and deposited numerous gravel.

I believe that the movement of gravel and other materials across playa surfaces is probably a more prevalent phenomena than has been generally recognized because of the exacting conditions needed to preserve scraper trails. I was surprised to observe the large number of playa-scraper trails on Rosamond, Rogers, and North Panamint Playas during the winter of 1967-68. Hundreds of trails were observed on these three playas. Although gravels probably frequently move across the playa surface, their passage is seldom recorded by trails for several reasons. (1) Water has to remain on the playa surface for a considerable period of time in order for the fine-grained sediments to become saturated. (2) Water on the playa lake must evaporate to a depth of an inch or less before movement can be recorded. (3) High wind conditions and/or ice formation must also be present. The above three conditions are not frequent enough on playas in western United States to record all of the movement of gravel across the playa surfaces. For example,

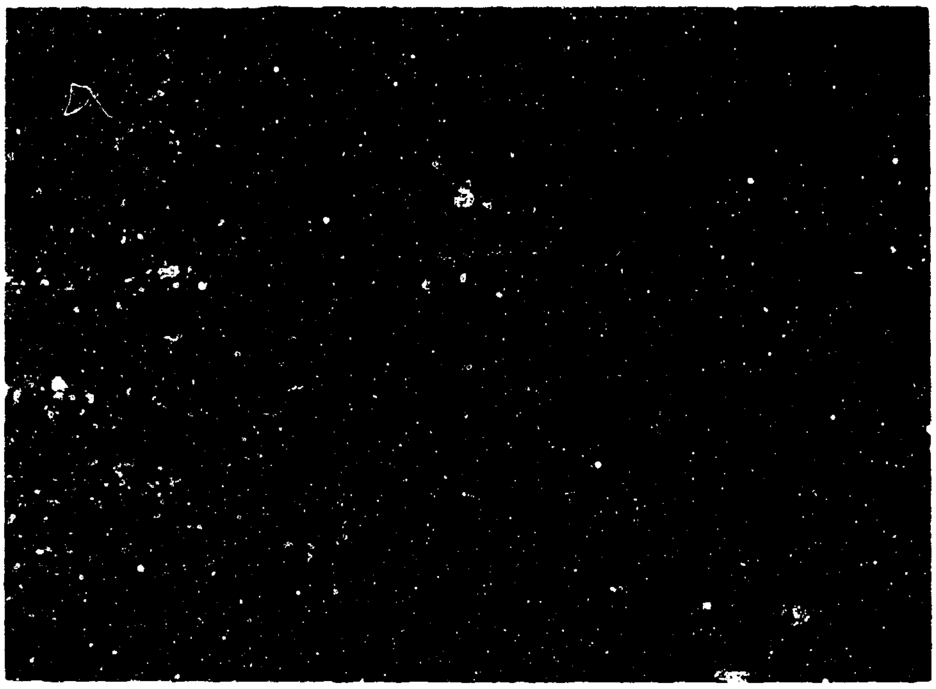


Figure 19. Playa scraper on North Panamint Playa forced out of its imbedded, resting position in surficial muds. Note hollow left by vacated gravel.

Figure 20. Numerous hollows left by vacated gravel along trend of Coyote Wash, Coyote Playa. The exacting conditions necessary for the formation and preservation of "scraper trails" were not present when the gravel vacated these hollows.

if a depth of water is much over one inch, waves in the water will smooth out the playa trails.

The overall effect of the mass movement of playa scrapers is to move the gravel clasts toward the playa margins and onto the desert flat. The ready movement of gravels across the playa surface helps explain one of the basic questions of playa geology--that is, why are playas barren areas? When one considers the amount of gravel brought onto many playas by flash floods, especially on long, linear playas such as North Panamint Playa, it becomes apparent that a mechanism of removal of gravels from the surface is needed to explain the continuation of the barren surface.

PLAYA EXPANSION AND SLOPE RETREAT

Many playas in western United States have expanded in size at the expense of the adjacent desert flats. In addition, microplayas have formed and coalesced in the desert flats adjacent to some playas. The expanded playas include those underlain by silt and clay characterized by slow capillary discharge (fine-grained playas) and those underlain by silt and sand characterized by relatively rapid discharge (coarse-grained playas).* Rabbit Playa, North Panamint Playa, and Stewart Valley Playa are expanded fine-grained playas which are discussed below (Fig. 21).

Numerous small irregularly-shaped and dark areas, some of which are slightly depressed, occur on the east side of Rabbit Playa. The light reddish-brown areas contrast to the predominantly buff-colored playa surface. The areas are more subject to erosion than other parts of the playa surface because of their softer sediments--they lack the hard crust of calcareous clays and silts characteristic of the surrounding playa (Fig. 22). The irregular reddish-brown depressions grade eastward into depressions with living xerophytes; these in turn grade into the typical desert flat characterized by numerous xerophytes. On the desert flat, the xerophytes are growing on sands interspersed with granules and small pebbles. Expansion of Rabbit Playa is probably the result of the decrease in the vegetation cover which held the sands and gravel of the desert flat in place. The sand and fine gravel appear to have been largely removed by wind from the former desert flat, although small isolated areas of gravel remain along the playa margin. Wind deflation must have increased greatly following the

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*Playas studied in this investigation that show evidence of expansion include Rabbit, North Panamint, Lucerne, Melville, Coyote and Troy Playas, California, and Red Lake, Stewart Valley, Big Smoky, and Clayton Playas, Nevada.

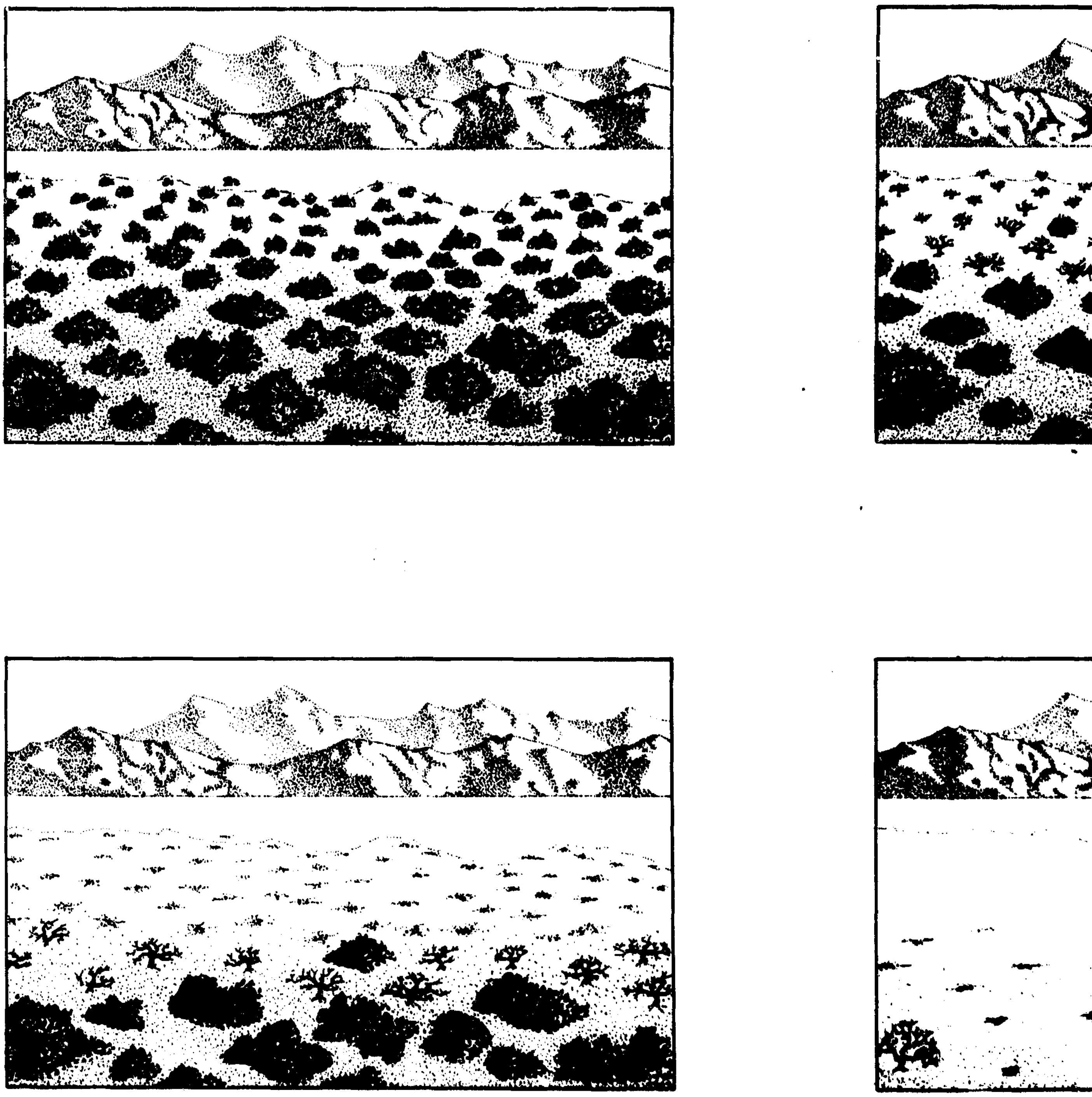
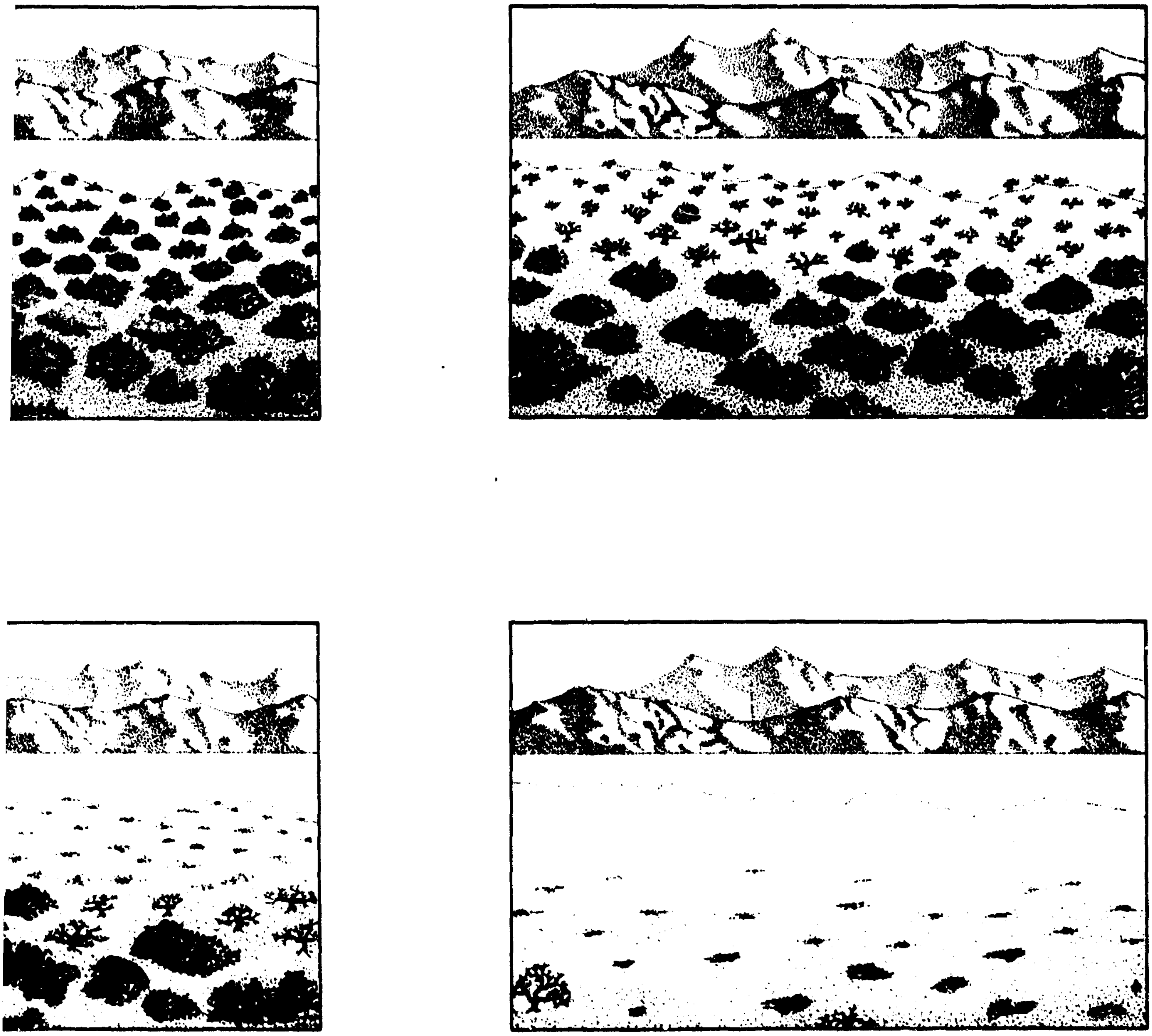


Figure 21. Diagrams showing expansion of playa surface at expense of desert flat. Adapted from Neal and Motts (1967, Fig. 9).

A



expansion of playa surface at expense of
ıal and Motts (1967, Fig. 9).

B

Figure 22. Darkened depression on Rabbit Playa, California, that was former site of vegetation growth.

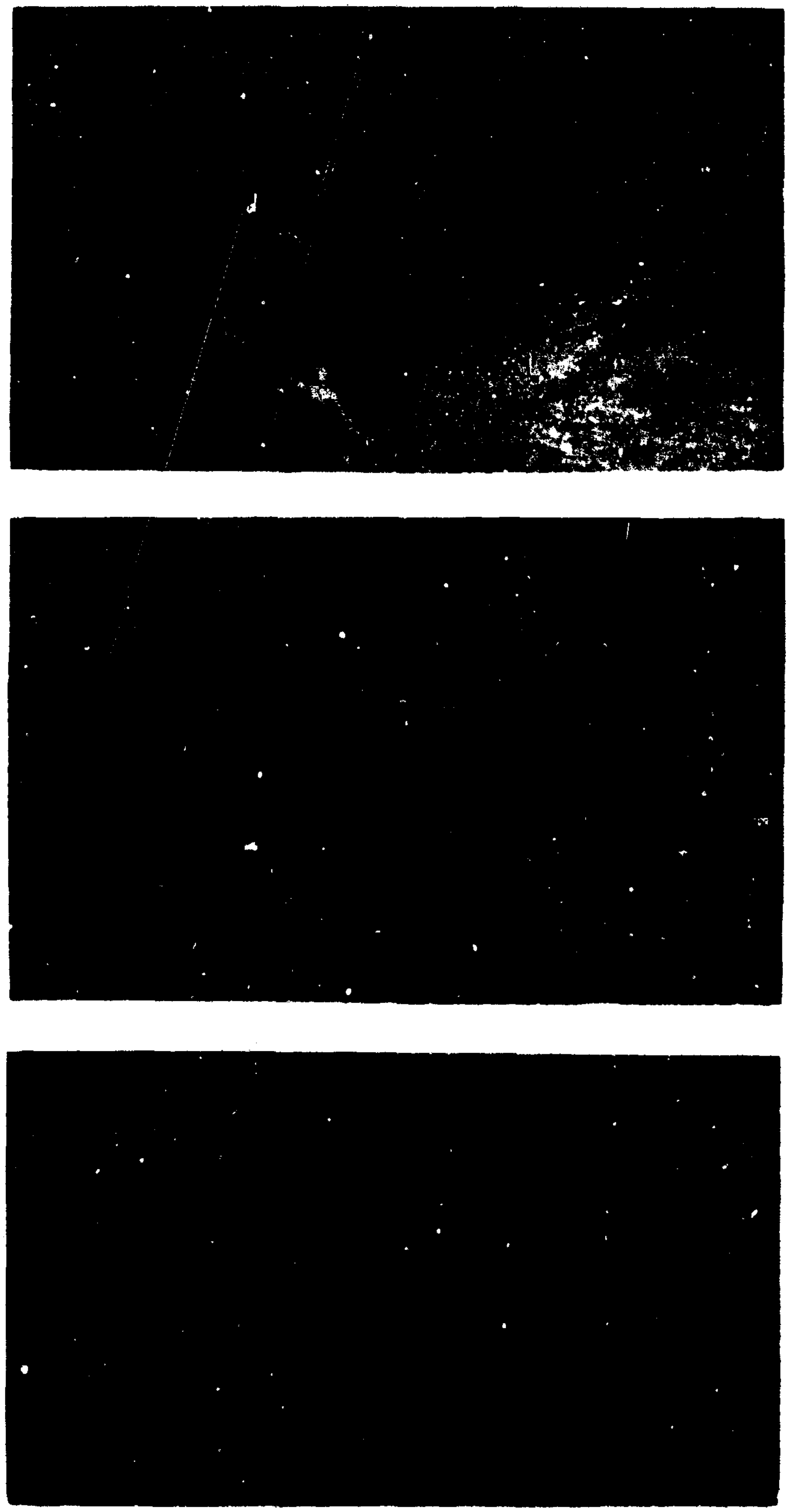
Figure 23. Salt-encrusted oval areas on North Panamint Playa, California, that were former sites of vegetation growth.

Figure 24. Close view of a barren oval area. Note puffy ground which is white and salt encrusted. This former site of vegetation has higher permeability probably because of the disruptive effect of roots.

decrease of the vegetation cover--a decrease that may have been caused by a smaller amount of precipitation and soil-water infiltration necessary to sustain plant growth.

Excellent geologic evidence of expansion may be observed at North Panamint Playa and Stewart Valley Playa. North Panamint Playa is long and narrow in comparison with its width; it varies from less than 1/2 mile to a little more than 1 mile in width and it is about 12 miles long. The southern half of the playa, especially south of Highway 190, is characterized by circular and oval areas ranging from a few feet to as much as fifteen feet in width (Figs. 23 and 24). Some areas are slightly raised, others are depressed; and most have puffy, salt-encrusted ground. Some oval barren areas are near oval areas in which there are living phreatophytes, suggesting that the barren areas also at one time contained these plants. In a similar manner, on the east side of Stewart Valley, numerous barren depressions grade into those with living phreatophytes and the latter in turn grade into depressions with numerous phreatophytes (Fig. 25).

Some of the playas characterized by rapid capillary discharge, including Clayton and Troy Playas, also show evidence of expansion. Motts and Matz (Chap. 6, p. 226) conclude that the large expanse of knobby-soft ground in the southern part of Clayton Playa is a former site of phreatophytes in an ancient desert flat. When the phreatophytes died, the puffy ground became part of the barren playa area. Evidence for the expansion of Troy Playa is presented by Groat (Chap. 5, p. 181). The expansion of the sand and silt playas may be related to a decrease in vegetation cover, to an increase in ground-water mineralization that killed the desert flat vegetation, or to a lowering of water levels below the level necessary for phreatophytes to subsist.



A

B

C

Figure 25. Evidence of playa expansion on Stewart Valley Playa, Nevada. A. Depression containing a living phreatophyte--note depressions in background without phreatophytes. B. Zone of dead and dying phreatophytes grading to living phreatophytes toward mountains and grading into barren depressions in direction of playa center. C. Darkened barren depressions grading toward mountains into zone of dead and dying phreatophytes shown on B.

WIND EROSION AND DEFLATION OF PLAYA SEDIMENTS

Whether playas are aggrading or degrading by wind deflation has been subject to controversy. Blackwelder (1931) believed that playas are areas of deflation and he cited Danby Dry Lake as an example where playa and lake deposits have been removed by wind erosion. On the other hand, Stone (1956, p. 250-261) concluded that little to no wind erosion occurs on playas. He believes that playas are aggrading very slowly and estimated that the sedimentation rate of playas was about 3 inches per thousand years (p. 270).

All the authors of this publication agree that the sediments presently being deposited in the playas studied during this investigation are removed by wind erosion and that little to no aggradation is occurring. Furthermore, this author has concluded that the surfaces of some playas, including Rogers and Rosamond, are currently being lowered by wind erosion. Motts (1965, p. 82-84) suggests that some playas and depressions in southeastern New Mexico and western Texas are slowly aggrading, whereas those of the Mojave Desert and Nevada are not. The New Mexico and Texas playas are covered with water for longer periods of time than those in the Mojave Desert and Nevada; in other words, they have a higher "flooding ratio" (Chap. 1, p. 9). Water in these playas not only acts as a higher base level but also prevents the deposited materials from being eroded by wind.

Although deflation and wind erosion apparently are effective on all playas of the Mojave Desert, the geologic and hydrologic processes accompanying deflation are somewhat different for each playa type. Deflation on coarse-grained and crystal-body playas is intimately related to lowering of shallow water levels which causes a complex sequence of events including solution-enlarging of sink holes and deflation of salt shreads precipitated

by capillary discharge (Motts, 1965, p. 101). In this chapter only the deflation of fine-grained playas will be discussed.

Deflation of fine-grained playas is accomplished by the formation, destruction, and removal by wind of concave-upward polygons or "mud curls." Mud curls are of two types as the term is used in this report. (1) Sediments currently deposited in playa lakes form thin sedimentation units which dry, develop polygonal fractures, and ravel to concave shreads (polygonal shreads) on the order of a few to several millimeters thick. (2) Long-term flooding of some fine-grained playas is followed by formation of thick (several millimeters to several centimeters) concave polygons or mud saucers from the massive clay bed of the playa. Deflation processes currently appear to be lowering surfaces of Rogers and Rosamond Playas, California, through the formation and removal of mud saucers.

Deflation of Sediments Transported into Fine-Grained Playas

Sediments transported by floods into the fine-grained playas studied during this investigation are deflated by wind soon after deposition. When I first visited Big Smoky Playa in 1963, much of the surface was covered with thin polygonal shreads (Fig. 26). All traces of the shreads had been removed when Walker (1966) mapped the playa two years later. On Big Smoky, Coyote, and other fine-grained playas, the author has observed the wind transport polygonal shreads by traction and suspension away from the sites of playa deposition. Although most of the shreads were probably removed by wind erosion, some may have been transported and redeposited by flood water.

Deflation of fine-grained playas studied during this investigation is aided by processes controlled by the difference in texture between the sediments currently being deposited and those deposited in the past under pluvial conditions. The overall texture of the currently deposited sedimentation units is coarser than the underlying fine-grained silt and clay that form a massive deposit of relatively uniform sedimentation profile, often hundreds of feet thick. The massive deposits were deposited in lakes during a more humid climate when more clay minerals were forming in the upland source areas. On the other hand, the streams are now depositing more sand and silt than clay, resulting in a textural discontinuity with the underlying massive clay.

The sediments now deposited in ephemeral playa lakes commonly form thin sedimentation units characterized by graded bedding, as shown by observations at Rogers Playa, Rosamond Playa, and Big Smoky Playa. Near the margin of the latter playa the basal part of the sedimentation units consists of sand and coarse silt which grades upward into fine silt, whereas

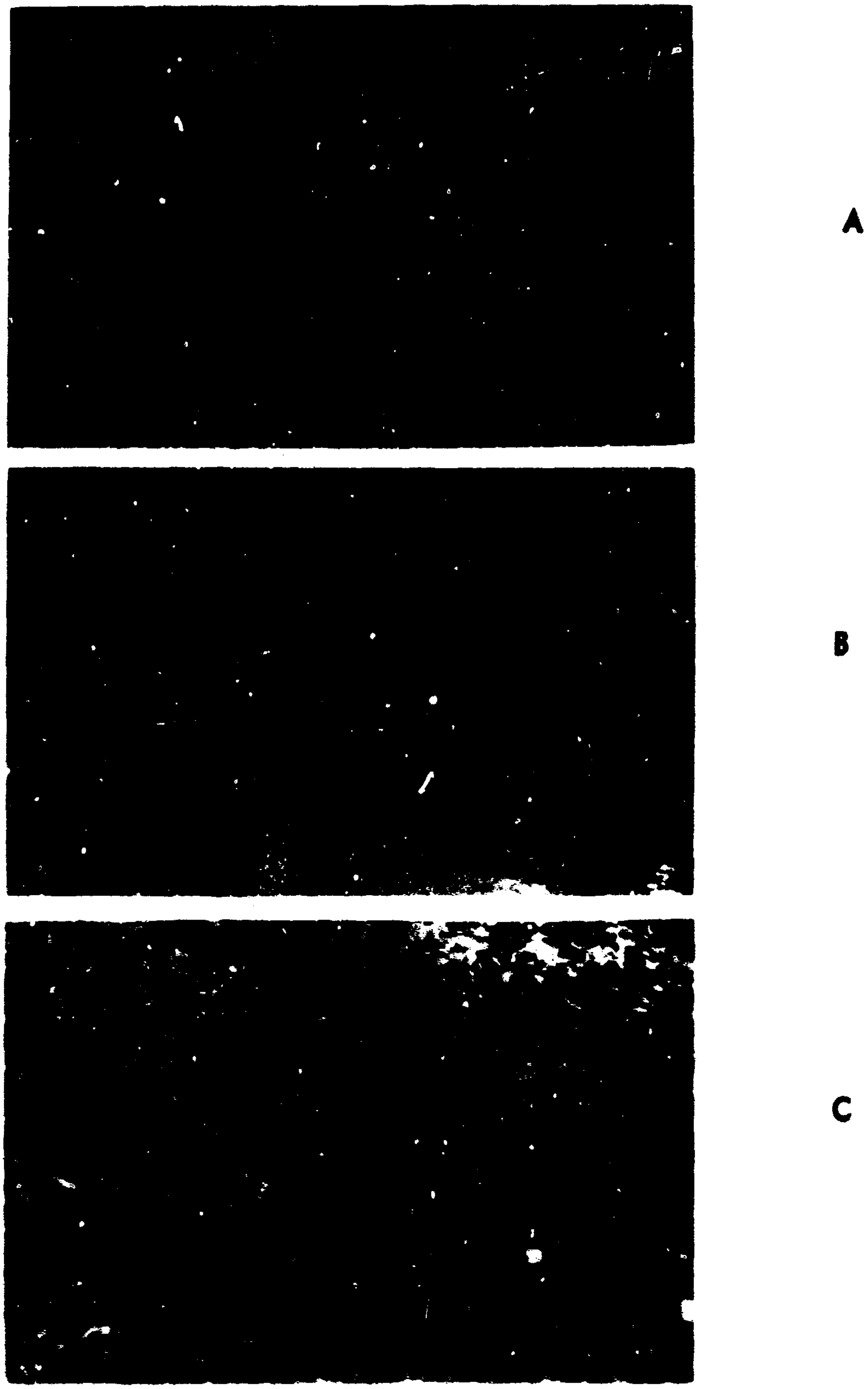


Figure 26. Erosion and deflation of polygonal shreads. A. Polygonal shreads covering large area of Big Smoky Playa in 1963. These shreads were entirely removed by deflation in 1965. B. Area of hard surface with convex polygons grading into surface of polygonal shreads on Rogers Playa, August 1969. The location of polygonal shreads appears to relate to the depth of water and length of time water remains on the playa surface. C. Close-up showing ravelling of polygonal shreads. Note that some shreads have already been removed by wind erosion.

near the center of the playa the entire sedimentation unit consists of silt with little sand (Walker and Motts, Chap. 4, p. 159). The upper part of the units is composed of fine-grained sediments which settles out of suspension much more slowly than the coarser deposits at the base of the units. The fine-grained deposits of high porosity and shrinkage coefficient dry and contract more than the basal deposits of lower porosity. This greater shrinkage of the upper part causes the formation of the concave polygonal shreads. Because of the textural discontinuity between the polygonal shreads and the underlying massive clays and silts, the shreads shear away from the underlying more massive material. The disconnected and loose shreads are easily eroded and transported by the wind.

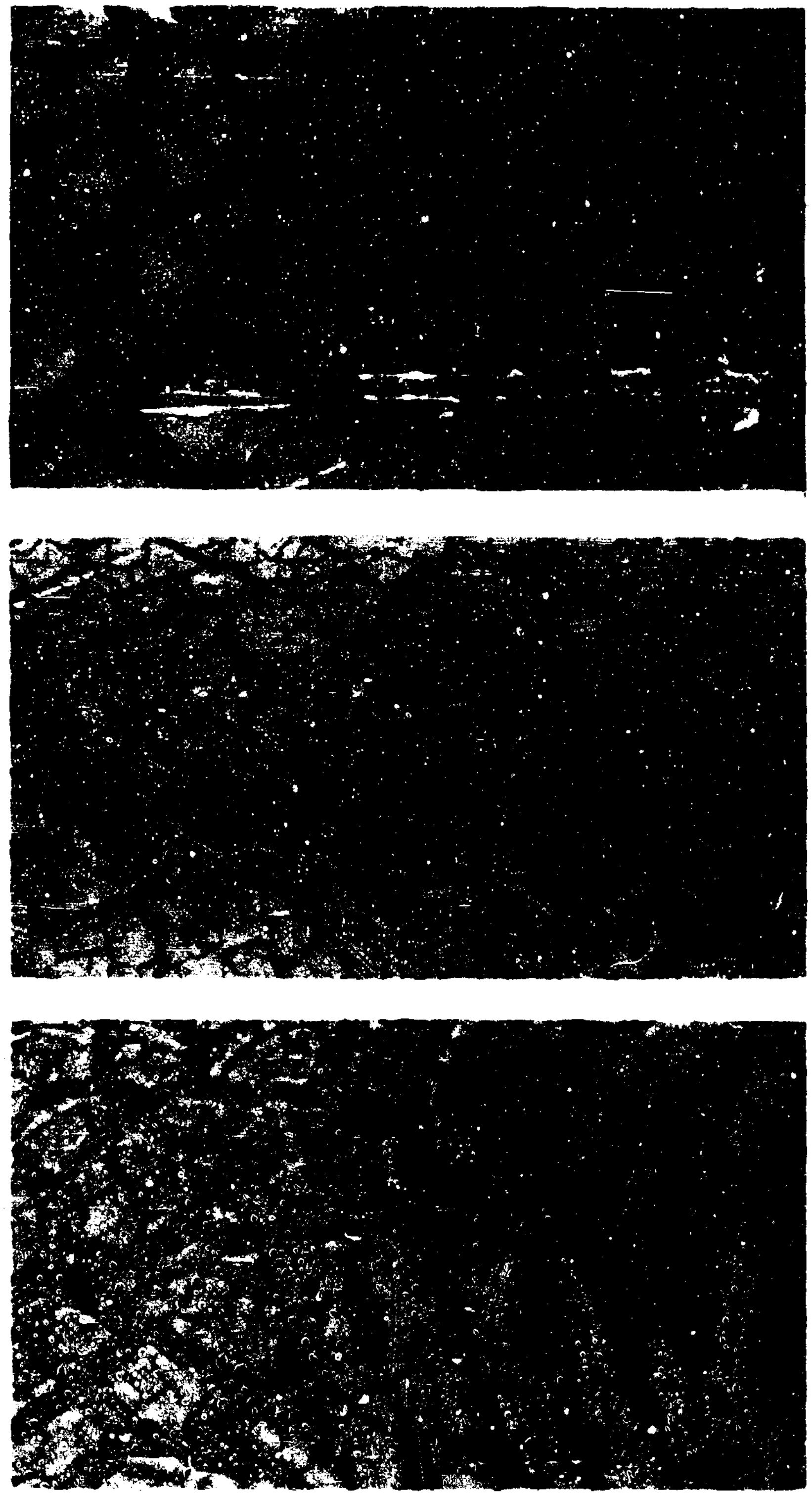
Wind Erosion Lowering Surfaces of Rogers and Rosamond Playas

Surfaces of Rogers Playa and Rosamond Playa are slowly being eroded and lowered by wind erosion. This is accomplished by hydrologic processes breaking down surficial sediments of the playas into smaller and smaller fragments which are loose and prone to deflation. The silts and clays of Rogers, Rosamond, and Buckhorn Playas are a coextensive unit deposited in ancient Lake Thompson; however the surface of Buckhorn Playa has a higher topographic elevation (2,286 feet) than either the surfaces of southern Rogers Playa (2,270 feet) or Rosamond Playa (2,271 feet). Because Buckhorn is located nearer the center of ancient Lake Thompson, the playa surface should be lower or at least at the same elevation as the surfaces of Rogers Playa and Rosamond Playa. The surface at Buckhorn Playa probably is higher because it has been protected from rapid erosion by abundant desert vegetation scattered throughout the general playa area, whereas the extensive barren surfaces of Rosamond and Rogers are subject to the intensive erosional processes discussed below.

Wind erosion on Rogers and Rosamond Playas is accomplished by the formation and destruction of polygonal shreads and "mud saucers" (Fig. 27). Mud saucers formed during a single storm vary considerably in thickness. Saucers are thicker in those parts of the playa covered by water for a relatively long time, including depressed parts of the surface (see Motts and Carpenter, Chap. 2, p. 42, 43).

Mud saucers have an upper fine-grained part and a lower coarse-grained part, as do polygonal shreads. Table 2 shows textural analyses of the upper and lower parts of mud saucers taken near Rosamond 1 and 2 test holes as well as analyses of samples taken at depth from these latter test holes and from other selected test holes on Rogers Playa during the summer of 1966. Table 3 shows textural analyses of the upper part of saucers from locations on Rosamond Playa (Fig. 28). The data from these tables support conclusions reached in the field that the sediments in the lower part of the saucers are coarser than the sediments in the underlying silt-clay blanket, and indicate that the upper part of the saucers generally are finer-grained than the sediments in the massive silt-clay blanket. The very fine-grained upper part of the mud saucers contracts most upon desiccation, thus causing the concave curling of the polygons.

The following mechanism may explain how mud saucers are formed. Flood water enters the playa and becomes a weak natural electrolyte by taking a small amount of salt and carbonate into solution from contact with the playa clays. Salt and carbonate precipitate in the shallow playa sediments through evaporation of capillary and artesian water. Although detailed information on the amount of salt in the playa-lake water and in the surficial playa sediments is scanty, field observations as well as the data in Table 2 suggests that salt is concentrated in the upper part of the playa sediments.



A

B

C

Figure 27. Occurrence and deflation of mud saucers on Rogers Playa, August 1969. A. Destruction of thick mud saucers. Note formation of younger polygons on the older ones producing a "saucer on saucer" form. B. Photograph showing destruction and deflation of saucers, pencil lies in cavity of saucer that has been deflated. Note the multiple layering of the saucers which may have formed from two floodings of different depths. C. Destruction of convex polygons by the formation of a younger set of concave-upward polygons on the larger ones.

Table 2: Textural Analyses of Mud Curls and Samples Taken from Test Holes on Rogers and Rosamond Playas.

Test Hole	Depth	Percentages: Sand	Silt	Clay	Salt
Rosamond 1	Mud Curls				
	Upper Clay	0.196	2.710	97.094	
	Residual Sand	27.153	31.360	41.487	
	6'	1.339	8.087	90.554	
	15'	8.332	38.509	53.159	
Rosamond 2	Mud Curls				
	Upper Clay	0.923	2.497	96.580	
	Residual Sand	29.067	20.538	50.395	
	5'	0.257	8.211	91.532	
	25'	1.253	17.277	81.470	
	43'	6.857	11.743	81.398	
	115'	1.093	14.706	84.201	
	118'	2.319	21.106	76.575	
Rogers 15	3'	55.211	13.076	31.221	0.492
	10'	3.259	11.525	85.205	0.011
	28'	15.067	13.392	71.204	0.767
	46'	3.259	11.525	85.205	0.110
Rogers 10	Surface	12.717	9.194	78.089	
	1'	2.488	13.169	84.165	0.174
	19'	4.698	9.570	85.607	0.125
	34'	19.738	16.987	63.246	0.036
Rogers 8	3'	14.180	17.104	64.914	0.802
	11'	7.483	8.194	84.316	0.005
	41'	88.750	2.418	8.833	0.007
Rogers 7	24'	20.582	16.555	62.863	
	64'	6.457	21.397	72.146	

Table 3: Textural Analyses from Upper Part of Curls from Locations on Rosamond Playa Shown on Figure 28

	Percentages		
Map Number	Sand	Silt	Clay
1	5.488	11.802	82.710
2	3.656	4.438	91.906
3	0.063	3.993	95.944
4	4.277	5.123	90.600
5	1.411	4.286	94.303
6	7.966	6.372	85.662
7	0.236	2.976	96.788
8	1.717	3.214	95.069
9	4.576	3.676	91.750

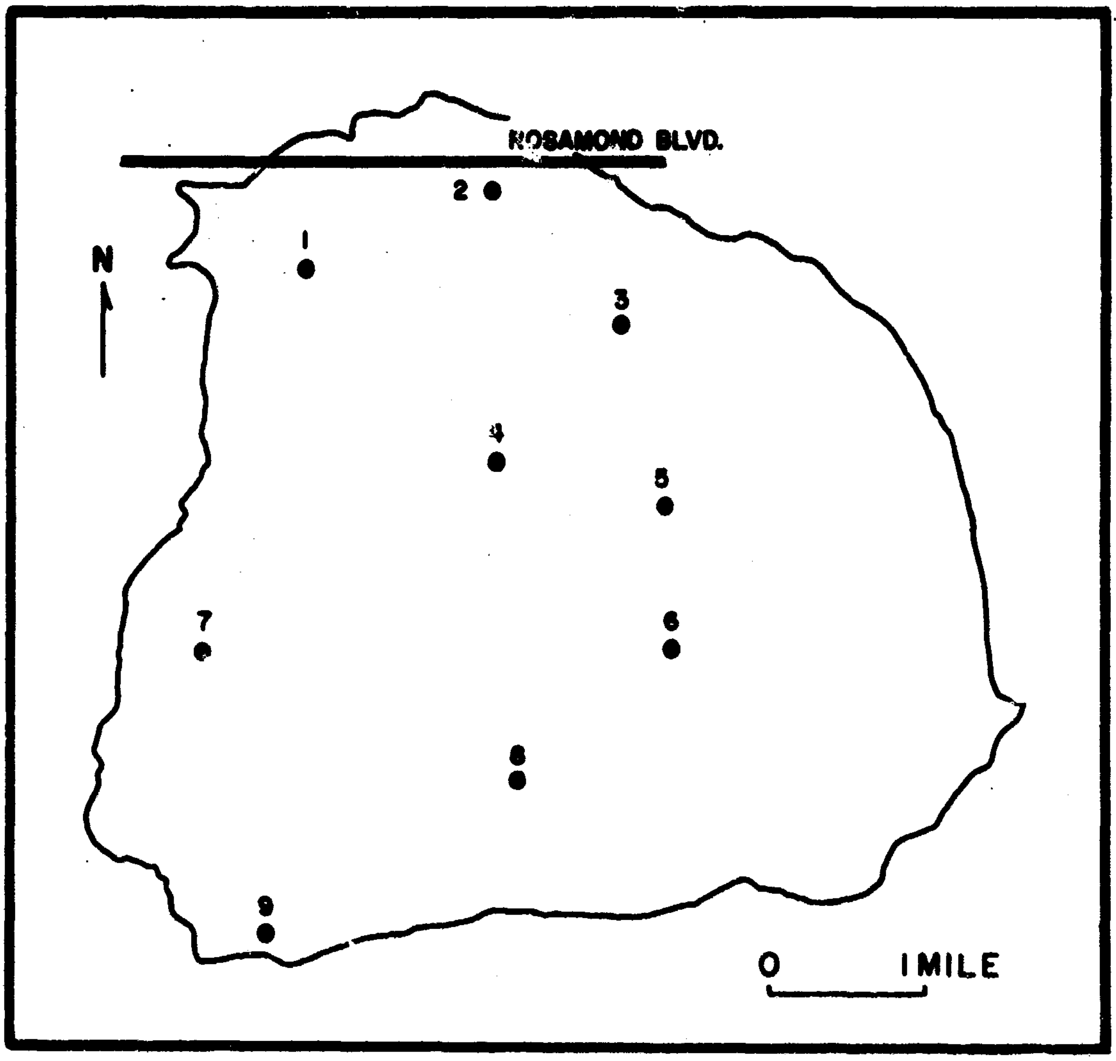


Figure 28. Sample locations of mud curls from Rosamond Playa, analyses of upper part of curls shown on Table 3.

Relatively large amounts of salt in solution produce a flocculating agent; however, a very small amount of dissolved salt and carbonate (which acts as a peptizer) tends to keep clay and fine-grained silt in a state of suspension and dispersion. Field observations support the above hypothesis. During a heavy rainstorm in the fall of 1967, the author observed that as soon as rainwater pools had formed on Rosamond Playa, the water became clouded with dispersed silt which may have moved into suspension along with the solution of salt. David Carpenter (personal communication) has also observed this rapid dispersion of surface clay into playa-lake water. Perhaps as salt and carbonate in the shallow sediments go into solution, the kinetic energy is sufficient to weaken and release some of the clay particles. When the playa lakes dry up, the clays in suspension settle to form the extremely fine-grained upper part of the mud saucers. Coarse silt and sand, brought into the playa lake during flooding, soon settle out to form the basal part of polygonal shreads and, at the same time, sand and coarse silt settle into semi-fluid playa clay to form the lower part of mud saucers.

The physical bonding characteristics of playa sediments may be modified by processes accompanying their saturation by flood water. These processes include the dissolving of salt and carbonate into playa water, the release of silt into the playa water, and the settling of sand and silt into the semi-fluid playa mud. The hydrostatic head of lake water may retard capillary discharge to build up capillary pressure in the shallow sediments. When the lake evaporates, release of capillary discharge promotes shearing of the shallow sediments.

As soon as they are formed, mud saucers become subject to further erosion, abrasion, and destruction because they shear away from the underlying massive clays and extend or "jut" above the playa surface. Moving

water from subsequent floods breaks the saucers into smaller parts and transports them across the surface (Fig. 27B). The subsequent floods also promote the formation of concave polygons within the larger ones, producing a "saucer within a saucer" (Fig. 27A). By these processes all clay saucers from a major flooding are destroyed and removed from the playa within a few years.

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13. ABSTRACT

The playas studied during this investigation may be divided into "fine-grained playas" (Rogers, Rosamond, Coyote Playas, California, and Big Smoky Playa, Nevada) and "coarse-grained playas" (Troy Playa, California, and Clayton Playa, Nevada). The "fine-grained playas" are characterized by: (1) deposits of medium silt through fine clay size, (2) slow artesian and capillary movement of water through the surface, (3) mostly smooth, hard surfaces, and (4) current formation of giant desiccation polygons in many of the playas. The "coarse-grained playas" are characterized by: (1) deposits of sand, silt, and in some cases evaporites, (2) rapid capillary discharge, (3) a water table that nearly coincides with the playa surface, and (4) soft, surficial sediments.

The surface morphology of most playas is related to several factors including the rate of capillary discharge producing puffy ground, and the frequency of surface-water flooding producing smooth, hard ground. Also, capillary discharge combined with deposition of mud from floods has transformed roots and water-transported plants into highly irregular knobby ground in some playas, including Clayton. Playas are dynamic landforms that change (1) over many years because of long-term climatic changes and man-made changes in the environment and (2) over a period of days or months because of short-term changes in precipitation and other climatic effects. A long-term change has been the expansion of many playas in recent years at the expense of their adjacent desert flats.

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